Handbook on
GOOD RADIATION PROTECTION PRACTICE IN INDUSTRIES INVOLVING NORM

Prepared by
IRPA TG on NORM

That all our knowledge begins with experience, there can be no doubt.

Immanuel Kant. The Critique of Pure Reason.

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FOREWORDS

CHRIS CLEMENT, IRPA PRESIDENT

The publication of this handbook on NORM is a major milestone for IRPA. It brings together the experience and expertise of some of the world's leading NORM practitioners and complements existing publications of ICRP and the IAEA.

NORM continues to be an important and growing issue for IRPA Associate Societies. As the world looks increasingly to the sustainable use of materials, including recycling, and to the development of raw resources for energy production, practical approaches for the management of NORM are more important than ever.

On behalf of IRPA, its Associate Societies, and practitioners around the world, I would like to express my sincere thanks to the members of the Task Group, who gave their time freely over many years to bring this important publication to completion. The persistence and collegiality of practitioners from across the world demonstrate the important role that IRPA plays in bringing people together around a common cause in radiation protection.

As President of IRPA, I am pleased to formally introduce this handbook. I trust that it will serve as a useful resource for practitioners for many years to come.

BERNARD LE GUEN, IRPA PRESIDENT 2021 - 2024

Since the establishment of this Task Group, I have been fully supportive and very enthusiastic about the IRPA NORM in Industries Task Group and the development of this handbook for professionals. Upon assuming the Presidency of IRPA in 2021, I ensured that the project received my full support, as well as that of IRPA and its Executive Council.

Enhancing international visibility and amplifying the voice of professionals were key priorities. In this context, and with the support of the two Chairmen, IRPA webinars were initiated to present progress on the Handbook on NORM. During this period, the Task Group and its individual members also increased their engagement in international forums, contributing the perspectives of NORM practitioners.

I was particularly encouraged by the emergence of "Team Africa," a subgroup dedicated to sharing African experience. The session held during the AFRIRPA Congress in Accra was especially successful. Since then, the group has continued its activities independently and remains an important voice for NORM in Africa. This regional expertise will be further strengthened with the establishment of the African NORM association and the Radon Associate, recently announced at the IAEA NORM XI conference in Accra, where the handbook was officially presented.

I would like to express my sincere appreciation to the co-chairs, Rainer Gellermann and Jim Hondros, for their tireless leadership, as well as to all members and contributors of the Task Group.

ROGER COATES, IRPA PRESIDENT 2016 - 2021

In 2018, following numerous requests from Associate Societies, the IRPA Executive Council endorsed the formation of the IRPA Task Group on NORM in Industries. This initiative recognized the growing awareness of NORM and its impacts in many industries and countries.

As someone who comes from a 'more conventional RP background (i.e., nuclear facilities), I was always aware that NORM issues require a very different and specific approach, and I was pleased to always defer to specialists such as Jim Hondros. The proposal to pull together a handbook specifically on NORM issues seemed like an excellent step forward for IRPA, and I was pleased to be able to give the launch of this project my full support. It is great to see this quality product from the Task Group, and especially pleasing to see the strong input from African colleagues.

Following the development of a terms of reference and consultation with Associate Societies, a call was made for members of a Task Group. Initially, there were 20 nominations, making this one of the largest IRPA Tasks Groups, highlighting the importance of NORM to Associate Societies. It was especially pleasing that many of the world's leading NORM practitioners made themselves available for the Task Group.

The clear message to the Task Group was to focus on practicality, with the aim of producing a document that was useful for practitioners from all over the world.

Rainer Gellermann and Jim Hondros, Co-Chairs of the IRPA Task Group

Members of an IRPA Task Group wrote this handbook. The members come from different regions of the world and have different professional backgrounds. They include staff members of authorities, researchers, consultants, and employees of industrial companies.

During the years we worked on this handbook, we learned that although we share a common basis for radiation protection, there are different interpretations even of the basic terms. Although the IAEA, as the central international organization, would like to limit the term NORM to materials that are subject to regulatory control due to their radioactivity, the term NORM is also applied to materials outside any regulatory control, like soil of the normal geogenic background. Other terms, such as TENORM, which the IAEA rejects, are nevertheless used (and understood) worldwide. In Chapter 2 of this handbook, we refer to these different perspectives in several places.

Although we all trust in the same physical laws of radiation, the fact that NORM is typically a mixture of many radionuclides with different physical and chemical properties presents a challenge. The radionuclides that can be easily measured and those necessary for a realistic dose assessment differ, and in the context of industrial processes, the complexity of NORM poses a demanding challenge.

As practitioners, we are neither teachers nor legislators. We have learned to tolerate different interpretations of individual issues. However, in our opinion, it remains essential to develop a common understanding of radiation protection that accepts different perspectives and approaches but takes into account the idea that the risks associated with activities involving NORM due to radioactivity can be kept low through simple measures and pragmatic radiation protection.

Radiation protection in industries involving NORM is part of the national radiation protection culture and is therefore embedded in a system of individual interpretations. Our discussions during the writing of the handbook have shown how important the historical, cultural, and economic conditions in which we work are. In Chapter 1 of this handbook, we have therefore attempted to describe some of these conditions.

We also found that practitioners' voices play only a minor role in the development of the radiation protection system. The active collection of experience, both good and bad (!) examples from practice, should be incorporated more strongly than before into the development of radiation protection. It is not enough to want to do good; it must also be implemented in a way that yields good results.

The IRPA, as a worldwide association of radiation protection societies in which practitioners are involved, has so far played only a minor role in the development of the radiation protection system. It would be desirable to give practical experience greater weight in the development of the radiation protection system. However, this presupposes that it is not only representatives of state research institutions and authorities who can participate in the international process of radiation protection due to the financial resources of these institutions.

As co-chairs of the IRPA Task Group on NORM for many years, we are thankful to all members of this task group who contributed to this text. The Handbook would not "be" without the tireless efforts of each of the TG members and other contributors, who, without hesitation, have freely given their time and expertise. Each Task Group member brought a range of different skills and experiences, which enabled us to learn from each other. We have acknowledged all individual contributions at the beginning of each chapter.

With the publication of the handbook, we extend our thanks to current and former IRPA Presidents and Executive members for their ongoing interest and support in the development of this Handbook.

During all of this year, one person has accompanied us as our 'advisor' from the IRPA Executive Council: Cameron Jeffries. Cameron, who, as well as contributing to the handbook, maintained a strong link with the IRPA Executive Council and represented the TG there. We would like to express our sincere thanks for this.

We also acknowledge the leadership of Roger Coates in establishing the Task Group and the subsequent unwavering support of Bernard and Chris.

While the handbook is freely available to all via the IRPA website, we would also like to sincerely thank the UK, German/Swiss, and Australasian Associate Societies for their financial support, which has enabled us to produce a limited number of hard-copy handbooks. Further hard-copy handbooks are available for purchase. The purchase price includes a modest additional amount, with all profits going to the IRPA Montreal Fund. The NORM TG members all agreed this was a way to support future generations of radiation protection professionals.

When we launched into this project, little did we realize the magnitude of the task! But we approached the challenge with dedication, passion, and energy.

We do not claim that this Handbook is perfect. Its purpose is to provide advice, assistance, examples, and confidence to practitioners. If there was one key takeaway, it is that NORM can be complex, and it is important to think through situations.

However, radiation protection continues to evolve. The ICRP wants to make it 'fit for purpose', and new technical developments are raising new issues. Nothing lasts forever, and if the considerable work that has gone into this handbook is to have an impact, then the IRPA also needs a group to continue the work, correct any errors that may still be hidden in the handbook, and keep the process going, without which there can be no good practice: the sharing of experiences.

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1 INTRODUCTION

Authors: Rainer Gellermann, Jim Hondos

Contributors: Phil Egidi, Stephane Pepin

Reviewer: Charles Wison

1.1 Purpose and aims of the document

Radiation protection is a system that has been developing for more than 100 years. With its beginnings in X-rays through medical and nuclear energy advances, the evolution has given the system many challenges. At the international level, the state of the art in science and research has been collected and evaluated by the UN-organization UNSCEAR since the 1950s. From this, the ICRP developed and continues to develop the framework concepts of radiation protection. The IAEA translates the concepts into standards that can serve as a basis for national legislation worldwide. Once we have a national legislative framework, radiation protection becomes the task of practitioners.

IRPA, as an organization representing radiation protection societies and, therefore, radiation protection practitioners, is involved with developments in radiation protection at two levels. On the one hand, the members of IRPA are the ones who implement radiation protection in practice. We work as researchers, the staff of regulatory authorities, as specialist experts, and as staff in companies with factories, mines, or other facilities. Together, we work to implement radiation protection. IRPA promotes the improvement of radiation protection by sharing experience and helping each other to ensure a good level of radiation protection.

On the other hand, the collective knowledge of IRPA, through the collection of experiences and evaluation of these experiences, is an important cornerstone in the further development of the radiation protection system (Figure 1-1).

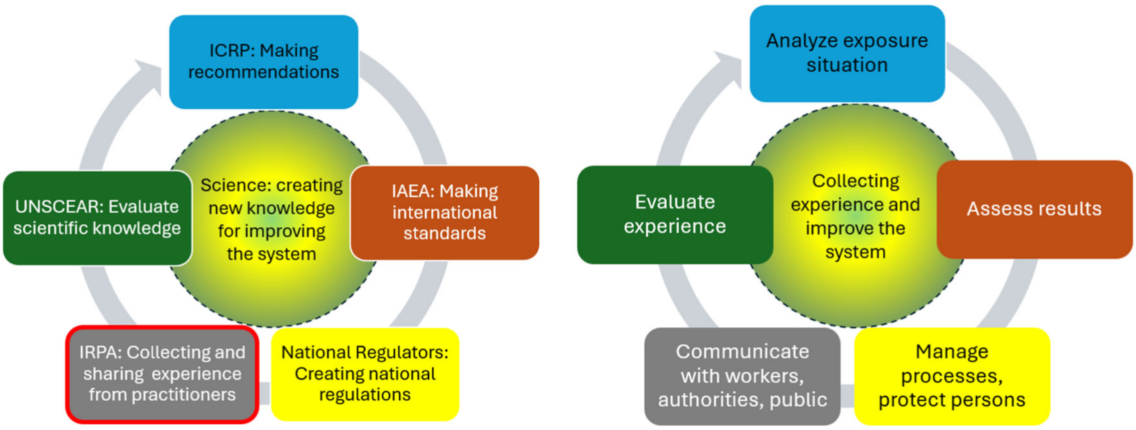


FIGURE 1-1: RADIATION PROTECTION AS A CYCLING PROCESS OF THE "WHOLE-SYSTEM-LEVEL" (LEFT SIDE) AND ON THE OPERATIONAL LEVEL OF RADIATION PROTECTION (RIGHT SIDE) (PICTURE AUTHOR: GELLERMANN)

This book aims to highlight these two sides of practical radiation protection for the field of naturally occurring radioactive materials (NORM) in industrial sectors, including mining. It is not intended to be a repetition of other handbooks, scientific texts, existing standards or regulations, but it aims to compile the experience gained in the application of the regulations.

The target audience of this book is other practitioners. It is a handbook and should not replace the laws and regulations of the countries within which you work. We hope you can use the handbook to gain a new perspective or an idea for a particular situation you might have. Whether you are a regulator, manager, operator, radiation protection officer, or worker, there will be something to deepen your knowledge or pique your curiosity.

This handbook should also be useful in countries or areas where regulations are being developed or are not yet fully in place. We are aware that, on a global scale, both the establishment of regulations and their implementation in practice are taking place at very different levels. Therefore, the book shall be of particular use to countries or regions new to NORM regulation or with limited resources.

1.2 How does ethics help us in practice?

The ethical foundation of radiation protection provides guidance on what we do and how we act as radiation protection practitioners. In practice, it means always striving to do the best for the right reasons.

We all have different moral codes rooted in personal values and beliefs; therefore, having a common understanding of the ethics of radiation protection is important, as the concept of radiation and its impacts can mean many different things to different people.

Box 1-1: Summary of the ethical framework for radiation protection (from ICRP 138)

1. **Beneficence/non-maleficence**: promoting or doing good and avoiding doing harm. This is reflected, for example, in the primary aim of the system of radiological protection to warrant an appropriate level of protection without unduly limiting desirable human actions.
2. **Prudence:** making informed and carefully considered choices without full knowledge of the scope and consequences of an action. Prudence is reflected, for example, in the consideration of the uncertainty of radiation risks for both humans and the environment.
3. **Justice:** fairness in the distribution of advantages and disadvantages. Justice is a key value underlying, for example, individual dose restrictions that aim to prevent any individual from receiving an unfair burden of risk.
4. **Dignity:** the unconditional respect that every person deserves, irrespective of personal attributes or circumstances. Personal autonomy is a corollary of human dignity. This underlies, for example, the importance placed on stakeholder participation and the empowerment of individuals to make their own informed decisions.

In May 2004, IRPA published its Code of Ethics [1], intended to aid members of IRPA Associate Societies in maintaining a professional level of ethical conduct in radiation protection. No. 9 of these Codes says: "*Professional reports, statements, publications or advice produced by members should be based on sound radiation protection principles and science, be accurate to the best of their knowledge and be appropriately attributed*". The consecutive codes call on the experts *to correct misleading, sensational, and unwarranted statements by others concerning radiation and radiation protection and to increase public understanding of radiation protection and of the aims and objectives of IRPA* and its Societies.

These requirements were guidelines for writing this handbook and are shown in Box 1-1. All radiation protection practitioners should be aware of these principles and seek to apply them in their work.

As practitioners, we operate within a system that has been developed over one hundred years. The system manifests as national, regional, and local legislation systems. Even though legislation may vary across countries, it establishes the rules by which certain activities (such as industries with NORM) are allowed to exist and operate.

We have obligations as radiation protection practitioners to ensure that the system is applied and implemented as agreed. In addition, we are obliged to protect people and the environment from the harmful effects of radiation to the best of our ability. Sometimes this requires us to go above and beyond the established system and have the courage to call out errors or inequities, and we do this through the established channels and by constantly contributing to the improvement of the system of protection.

As individuals, our own ethics and values also play a role in our actions. These might be different from the system that we need to implement, and we should be honest enough to acknowledge that.

Some ethical considerations in relation to NORM include the following.

- Naturally occurring radionuclides are part of our world, and we must accept the world as it was created. But "naturally occurring" does not necessarily mean "healthy" nor does it mean "not healthy". Prudence is necessary.
- The following facts must be kept in mind for risk assessments regarding NORM:
  - There is no risk of deterministic radiological effects.
  - Radiological emergencies can generally be excluded.
  - Potential radiation risk at these dose rates comes from chronic exposures.
  - There are often other (e.g., chemical) hazards and risks that need consideration, too.
- Industries dealing with NORM (including mining, water treatment, energy production) generally provide benefits to society and operate within an agreed legal framework. It is important to balance the benefits and the impacts. Constraining industries and activities where the radiation risk is low is as bad as allowing industries to operate unregulated.
- Finding a balance between protecting humans and the environment and missing out on the benefits of industry requires an agreed system based on risk assessment and management. Safety is a balance of all relevant risks, not only radiation. For example, personal protection may increase workers' personal burdens and other stress levels. But because no one can be an expert in everything, all disciplines must be able to cooperate and work as a team to make good decisions.
- While the boundary between natural background radiation and NORM is a fine line, the regulatory systems aim to be very clear-cut (for example, through exemption and clearance values and limits). This requires us to be considerate and prudent.
- Similarly, underemphasizing or overemphasizing radiation risks at very low levels, or even at background radiation levels, to less knowledgeable groups for any reason is unethical.
- Radiation protection is complex and can be confusing to people who do not have enough knowledge on the topic. For example, we are all familiar with the concept of "dose", however, it is not a measurable quantity and must be calculated. We need to recognize the complexity in our dealings with all stakeholders and aim to be clear and understandable.
- Respect for everyone's views is a vital characteristic of a good radiation protection practitioner. Acknowledging that everyone has a perspective and/or question that deserves attention is a hallmark of the principle of dignity. However, respect does not oblige

us to agree with all opinions. This is particularly true when opinions deviate significantly from the scientific foundations of our field.

- While dignity requires that we respect the personal views, opinions, and emotions of laypersons or workers, it is equally true that we should expect the same level of respect.
- In recent years, radiation protection has shifted from being a purely technical and objective discipline to a more subjective one, incorporating storytelling in a social framework. This should form part of the foundation of our approach to radiation protection.
- Dignity requires respect. Respect requires knowing the different roles of experts, workers and citizens (see Table 1 1) and being aware that every expert is also a worker and citizen in other fields.

TABLE 1-1: ROLES OF EXPERTS, WORKERS, AND CITIZENS IN COMMUNICATION

Experts	Workers	Members of the public
Know the specific risks of the competence field and judge rationale.	Are informed about risks at their workplace and want safe (healthy) workplaces.	May be unaware of the specific radiation risks in their fields of interest and judge emotionally.
Are responsible or at least co-responsible for the con-sequences of their doing so. (Ethics of responsibility)	Are responsible for their work but not for the consequences (Work ethic)	Are not responsible for the consequences of their demands. (Ethics of conviction)
Name technical possibilities and legal restrictions based on scientific and regulatory frameworks knowledge.	Know the technical possibilities and legal requirements for their field of work and answer questions if required.	Demand actions or the omission of actions that affect their interests.

As radiation protection practitioners, we face situations that require us to base our advice and decisions in an ethical, respectful, and logical manner. We know that this also includes the courage to make a stand when required and call out errors of fact or additional improvements in a dignified manner.

It is also important to be humble and, in some situations that we will not know, strive to find the answers.

1.3 What are the themes considered in this handbook?

The system of radiation protection is based on scientific knowledge and a national government decision to develop and implement a robust national framework of legislation. Within this framework, practitioners do their work, and this handbook aims to give them support based on a collection of international practitioners´ experiences.

In all countries worldwide, radiation protection is a component of national legislation. Minimum standards for governmental responsibilities and programs under ICRP 103 are set by the IAEA in its Safety Standards Series, GSR Part 1 [2]. However, there are many countries where NORM is not specifically treated in the national law. Part of the reason for this is that the right of regulation is delegated to regional governments (Federal states, territories), and their provisions may differ in detail. In all these cases, practitioners must answer questions, decide on actions, advise their employers, and contribute to ensuring good radiation protection. For these colleagues, this handbook may provide essential support.

This handbook deals with radiation protection in industries involving NORM. We know that man-made radiation sources are also used in these industries. However, this book focuses on NORM as the radiation source. Moreover, radioactive materials for use in building materials is not considered in this book.

As previously noted, it is important to note that this handbook is NOT a substitute for a regulatory system. Key themes and challenges that arise with NORM and are considered in this handbook include:

1. Chapter 1 discusses the aims and themes of this handbook as well as the fundamental ethics necessary for practitioners.
2. Good radiation protection requires that basic knowledge of the scientific basics, as well as concepts and terms of radiation protection, be understood and considered similarly. Chapter 2 describes these basics.
3. The term "industries involving NORM" highlights the fact that NORM is usually one component in an industrial plant. Effective radiation protection must focus on the relevant materials. To identify key radioactive materials in a processing facility, a good understanding of the processes is important. Chapter 3 deals with this.
4. Good radiation protection is the result of optimization. The most essential practical method of optimization is the Graded Approach ("GA"). Chapter 4 provides an overview of the GA.
5. Radiation protection must be based on sound facts. Appropriate characterization of NORM is the basis of all risk assessments (i.e., actual or possible doses) and is decisive for the development of any management strategies. Chapter 5 shows how this can be done directly with different types of measuring equipment and indirectly by using NORM-types.
6. As well as being radioactive, NORM often also contains chemically toxic substances. Therefore, the management of NORM requires an integrated approach that takes into account the risks of both types. In Chapter 6, the challenges related to this approach are considered.
7. Sustainability and the circular economy are important concepts for the plant, and radiation protection concepts are important contributors. In many cases, the mere mention of the word radioactive requires specialized disposal pathways; however, the actual risk might be miniscule. Some aspects of the complex theme are the content of Chapter 7.
8. A special field of radiation protection is transport. Here, the internationally hazardous goods regulations provide a detailed and complex system that must be applied. In Chapter 8, the requirements for NORM are extracted and described.
9. To achieve mutually positive outcomes between industry, authorities and the community, all parties need to understand their different roles and responsibilities. Good communication about their roles is key. (see Chapter 9).
10. Another special aspect of NORM is that products and consumer goods are traded that exceed the exemption values. Examples of such products are compiled in Chapter 10. Good radiation protection means, in this case, informing consumers, buyers, and other users about the radioactivity.

11. In a final chapter 11, we have collected some experience from the continents with the radiation protection related to NORM.

The Appendices contain some data that has been proven to help solve practical tasks.

Note that in this handbook, when references are made to regulated levels, such as limits, reference levels, or dose constraints, only general guidance is provided, as individual nations may have different values.

Training in all aspects of radiation protection is necessary for ensuring that effective advice and technical support are provided. For this purpose, many training courses and documents are available. This handbook does not focus on this item. Nevertheless, the experiences and views presented in this handbook give some useful comments in this regard.

The title of this book contains the phrase "Good Radiation Protection Practices". We used the word "good" to address that good radiation protection means effectively controlling exposure to keep radiation doses "As Low As Reasonably Achievable" (ALARA), protecting both people and the environment. Striving for the best may be an individual goal, but it needs to take into account the practical aspects.

As with each book, this handbook is not complete in all areas of radiation protection in industries. There are many other publications you can reference, including the extensive work of the IAEA and the ICRP, as well as published presentations from IRPA Congresses. Also, reach out to your fellow practitioners and ask for help or guidance.

2 RADIATION BASICS – INTRODUCTION TO RADIATION

Authors: Rainer Gellermann, Jim Hondos, Phil Egidi, Rosabianca Trevisi, Christian Kunze

Contributors: Saidou, Katerina Rovenska, Fidel Grandia, Analia Canoba, Margaret Chege, Jeakook Lee, Anne Cordelle

Reviewer: Charles Wilson (HPS)

2.1 Avoid the Mistakes!

In this handbook, we primarily focus on the practitioner's perspective in mining, oil and gas, water treatment, and other industrial processes involving radioactivity of natural origin. NORM can be present in ores, feedstocks, solids, sludges, filters, raffinates, and other liquids; some NORM isotopes are volatile and can't be incinerated. The following chapters present some essential basics that shall help you to avoid the following **mistakes:**

1. Drawing conclusions on incomplete analysis of radionuclides contained in NORM to only those few you might have determined by simple gamma-spectrometry. There may be other radionuclides that need to be considered.
2. Assuming wrong radioactive equilibria in the decay series where disequilibria exists.
3. Application of indices or factors for radiation protection purposes that do not meet the conditions for workplaces.
4. Making conclusions about cancer risks as a non-expert in radiobiology or epidemiology.
5. Not sampling or evaluating liquids and air emissions, other environmental monitoring leading to incomplete assessment of pathways and receptors.

To avoid these mistakes, the following items need to be considered:

- Complete measurement of all decay series radionuclides is neither feasible nor necessary. If you understand the decay chains that are present, then you may be able to make some assumptions about the presence or absence of each radionuclide in the chain. You must deal with the data that can be obtained in an individual case.
- Understanding that the natural decay series consists of radionuclides with different half-lives from different chemical elements, with different chemical properties.
- The physical laws describing decay and ingrowth of radionuclides in the decay series are crucial for interpreting the radionuclide composition of NORM from measuring results (see Chapter 2.2.4).
- The physical and chemical properties of the radionuclides rule the behavior of radionuclides in industrial processes. Based on these properties, the composition of NORM can be anticipated if the physical and chemical processes of the specific case are known.
- Our roles involve physics, chemistry, and biology. To put simply, radioactive decay happens in the nucleus (physics), the fate and transport in the environment is a function

of electrons sticking and not sticking to each other (chemistry), and when it comes near or in you, then we worry about dose (biology).

- If you end up inheriting a legacy NORM site that is contaminated but with little documentation, then a structured and approved sampling and analysis plan with accompanying health and safety plan (and Quality Assessment/Quality Control – QA/QC plan) should be required. Input from stakeholders is welcome; however, they inform decisions, they do not dictate decisions. That is left to the relevant competent expert and the appropriate regulatory body.
- Cosmic rays and cosmogenic radiation are not part of this handbook, but one should be aware of their existence so as not to interfere with measurement.

2.2 Terms, Radionuclides, Definition NORM

2.2.1 What is Radioactivity?

Radioactivity refers to the physical phenomenon of the spontaneous transformation ("decay") of atomic nuclei ("radionuclides"). The most important modes of radioactive decay for natural radionuclides are (see Figure 2-1):

- Alpha decay (α-decay): the nucleus emits an α-particle (He-4 nucleus);

  Example: Ra-226 → Rn-222 + α

- Beta (minus) decay (β-decay): the nucleus emits an electron (β-Particle) and an antineutrino

  Example: Th-234 → Pa-234 + $\beta^{-} + \overline{\nu}$

- Electron capture (EC): the nucleus captures an electron from the atomic shell and emits a neutrino. X-rays occur as accompanying radiation.

  Example: K-40 + e^{-}→ Ar-40 + ν (but there is another decay mode via Beta decay: K-40 → Ca-40 + $\beta^{-} + \overline{\nu}$

Gamma radiation is the (electromagnetic) photon radiation emitted by the newly generated nucleus due to its energetic excess, i.e., gamma is a result of radioactive decay.

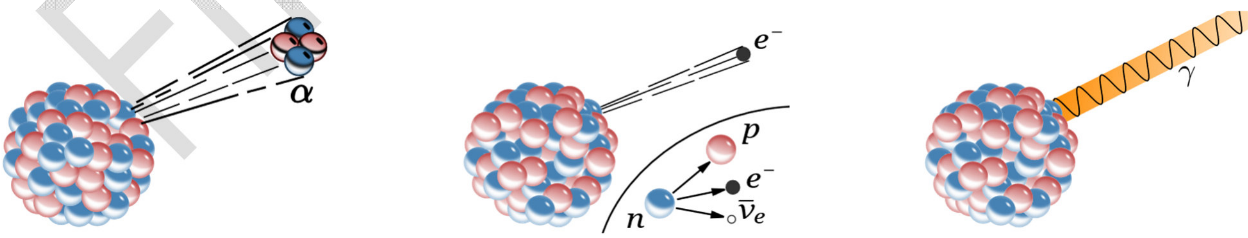


FIGURE 2-1: RADIOACTIVE DECAY MODES OCCURRING IN NORM AND GAMMA EMISSION

Source: Wikipedia 2025; cc-License

The radioactive decay process and the accompanying gamma rays are random but highly predictable (stochastic).

The following physical terms are used to characterize radioactivity:

Activity (A): The number of nuclear transformations/decays per unit of time. SI-unit of activity: Becquerel Bq. 1 Bq = 1 decay per second [s^{-1}]. Old unit: Curie (Ci). The following applies: 1 Ci = 37 GBq; 1 pCi = 37 mBq.

Activity concentration (C): Activity per mass or volume [Bq/kg] or [Bq/m³].

Specific activity (SA): SA is defined as the activity per unit mass of a radionuclide and is a physical property of that radionuclide. SA is benchmarked to Curie (Ci) or Becquerel (Bq) of activity in Table 2-1. It is related to the atomic mass number and half-life (or decay constant) of the radionuclide.

Half-life ($T_{1/2}$) is the time required for an activity or activity concentration to reduce to half of its initial value by radioactive decay. It is a physical constant for each radionuclide that external physical or chemical effects cannot modify.

The concept of specific activity (SA) reflects one major difference between working with chemical contamination and radioactive contamination. The SA can vary by orders of magnitude between radionuclides. For example, 1 Curie of U-238 has a mass of almost 3 Mg (tons). By contrast, 1 Curie of Ra-226 weighs only 1 gram, and the mass of 1 Ci of Po-210 is only 0.2 milligrams!

Table 2-1 shows the specific activity of the common Naturally Occurring Radionuclides (NOR). Please note: The activity in 1 gram of the pure chemical element of uranium and potassium in its natural isotope composition differs and is given in Table 2-2.

Additionally, in Table 2-1, the number of atoms of a radionuclide in 1 gram NORM with 1 Bq/g is given. This column demonstrates that only a very limited number, down to a few thousand atoms, of very short-lived radionuclides like Pb-214 and Bi-214, are needed for 1 Bq/g.

TABLE 2-1: SPECIFIC ACTIVITY OF THE COMMON NOR

Radionuclide (RN)	Half-life [years]	Mass of 1 Ci	Specific activity [µCi/g]	Specific activity [Bq/g]	Number RN-atoms in 1 gram NORM with 1 Bq/g
Th-232	1.405×10^{10}	9.1 Mg	0.11	4,055	6.40E+17
U-238	4.471×10^{9}	2.98 Mg	0.34	12,430	2.04E+17
U-235	7.038×10^{8}	463 kg	2.16	79,973	3.20E+16
K-40	1.25×10^{9}	140 kg	7.15	2.65E+05	5.69E+16
Ra-226	1601	1.01 g	9.88E+05	3.66E+10	7.29E+10
Ra-228	5.75	3.67 mg	2.73E+08	1.01E+13	2.62E+08
Po-210	0.378	0.22 mg	4.51E+09	1.67E+14	1.72E+07
Rn-222	0.011	6.56 µg	1.52E+11	5.64E+15	4.81E+05
Bi-214	3.78E-05	23 ng	4.42E+13	1.63E+18	1723
Pb-214	5.15-05	31 ng	3.24E+13	1.20E+18	2346

2.2.2 Where does natural radioactivity come from?

All chemical elements were generated in the early stages of the cosmos. Elements from hydrogen up to iron (Fe) were generated in (former) stars. Elements with atomic numbers greater than 26 (Fe) were created in supernovae or neutron star collisions and distributed throughout the galaxy. As dust clumps together through the process of accretion, planets form. Eighty-four elements formed in these early stages of the solar system are still found in the Earth's crust, many at trace levels. Where the elements concentrate in economic deposits, the term "ore" is used.

Chemical elements consist of nuclides with the same number of protons (Z). Nuclides of a chemical element with different mass numbers are named "isotopes". About 250 isotopes are stable, about 20 are radioactive but have such long half-lives that they still exist (Table 2-2). These radionuclides are called **primordial.**

TABLE 2-2: PRIMORDIAL RADIONUCLIDES (DATA TAKEN FROM WIKIPEDIA; ACTIVITY CONCENTRATIONS CALCULATED BY THE AUTHORS)

Radionuclide	Decay mode	Half-life	Abundance in the pure element	Activity concentration of the pure elements
		Years	%	Bq/g
K-40	β−, ε, β+	1.25E+09	0.012	31.8
Rb-87	β−	4.97E+10	27.83	852
Cd-113	β−	7.70E+15	12.23	0.002
In-115	β−	4.40E+14	95.72	0.250
La-138	ε, β−	1.02E+11	0.089	0.836
Nd-144	α	2.29E+15	23.8	0.010
Sm-147	α	1.06E+11	15	127
Sm-148	α	7.00E+15	11.25	0.0014
Gd-152	α	1.10E+14	0.2	0.0016
Hf-174	α	2.00E+15	0.16	0.00006
Lu-176	β−	3.76E+10	2.59	51.7
Os-186	α	2.00E+15	1.59	0.0006
Re-187	β−	4.12E+10	62.6	1,075
Pt-190	α	6.50E+11	0.012	0.013
Bi-207	α	1.9E+19	100	3.3E-06
Th-232	α, SF	1.41E+10	100	4,058
U-235	α, SF	7.04E+08	0.71	568
U-238	α, SF	4.47E+09	99.9	12,426

From a radiation protection perspective, many primordial radionuclides can be disregarded. This holds independently of the high activity concentrations of some of the radionuclides in Table 2-2 (e.g. Re-187, Rb-87) because of the low doses they cause in all circumstances. Only U-238 (with U-235), Th-232, and K-40 are considered relevant for radiation protection (RP) reasons.

The radioactive decay of the **primordial radionuclides** Th-232, U-238, and U-234 produces other **radiogenic radionuclides**. These radionuclides have shorter half-lives and are present on Earth because they are continuously generated by the decay of primordial nuclides. Well-known radiogenic radionuclides are Ra-226 and Po-210. Lesser-known but relevant to radiation protection are Ra-228 and Pb-210.

However, several other radionuclides, such as tritium (H-3) and radiocarbon (C-14), are also continuously produced, not from radioactive decay but by cosmic radiation. These **cosmogenic radionuclides** in their natural activity concentrations cause only very low doses (C-14 about 12 µSv per year [3]). They are not significant from an RP perspective.

A fourth group of radionuclides is **artificial, or man-made**. These radionuclides are deliberately produced in accelerators or nuclear reactors or are generated as waste. They can occur at very high activity concentrations and require appropriate radiation protection. Therefore, the radiation protection system, which in its early stages was focused on X-rays and radium, needed to adapt to account for artificial (man-made) radionuclides.

Terms that summarize primordial and radiogenic radionuclides are:

- **Radionuclides of natural origin** (IAEA Glossary [4]): Radionuclides that occur naturally on Earth <u>in significant quantities.</u>
- **NOR,** for naturally occurring radionuclides (in any amounts).

Cosmogenic radionuclides are not considered to be radionuclides of natural origin within the IAEA definition.

Note that some radionuclides that occur in nature can also be man-made. An example is Po-210, which is used in static eliminators. In such cases, for radiation protection, the radionuclide's provenance determines whether it is NORM or man-made.

A special case is the mining and processing of uranium or thorium ores. These activities are considered by the IAEA (cf. [4], [5]) as a part of the nuclear fuel cycle.

Man-made radiation sources are also used in industries involving NORM for their ionizing radiation (e.g., for level measurements). However, they are handled under a planned, licensed program (for example, companies may have to maintain them and their paperwork).

An overview of all modes in which radionuclides are generated is shown in Figure 2-2.

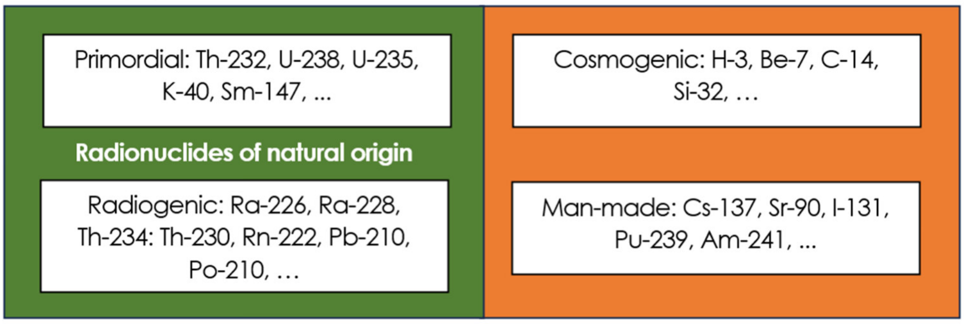


FIGURE 2-2: RADIONUCLIDES OF NATURAL ORIGIN ARE PART OF THE FOUR MODES IN WHICH RADIONUCLIDES ARE GENERATED.

2.2.3 What is "NORM"?

NORM is the acronym for **Naturally Occurring Radioactive Material**. The term developed from several acronyms introduced in the 1970s and 1980s to describe relevant exposures from radiation sources of natural origin. The term "NORM" was used several times in 1997 in the presentations of the "International Symposium on radiological problems with natural radioactivity in Non-Nuclear Industry" [6]. However, the use was ambiguous and included all naturally occurring radioactivity without its relevance from a radiation protection point of view.

In the US, the "NAS Committee" defined TENORM as "*any naturally occurring material not subject to regulation under the Atomic Energy Act whose radionuclide concentrations or potential for human exposure have been increased above levels encountered in the natural state by human activities*" [7]

The ICRP in the ICRPedia defines NORM as "*Material containing no significant amounts of radionuclides other than naturally occurring radionuclides, that may be raw material or material in which the activity concentrations of the naturally occurring radionuclides have been changed by some process.*" [8]

In its Glossary [4], the IAEA defined NORM as "*Radioactive material containing no significant amounts of radionuclides other than naturally occurring radionuclides.*" Three explanations supplement this definition:

1. The exact definition of 'significant amounts' would be a regulatory decision.
2. Material in which the activity concentrations of the naturally occurring radionuclides have been changed by a process is included in naturally occurring radioactive material.
3. Naturally occurring radioactive material or NORM should be used in the singular unless reference is explicitly being made to various materials.

A phrase in this definition is "naturally occurring radionuclides". This phrase can be abbreviated "NOR", and using this term, the term NORM can be understood as shown in Figure 2-3. The scheme in this figure illustrates:

- NORM consists of two different components: naturally occurring radionuclides (NOR) and non-radioactive material "M".
- Naturally occurring radionuclides (NOR) make the radioactivity and are physically quantified as activity (in Bq).
- "M" represents the other components that make up the overwhelming part of the mass (in g or kg or Mg = tonne = metric ton).

Understanding the activity concentration (activity divided by the mass) of a material is very important because, according to the IAEA, a material becomes "NORM" only if the activity concentration exceeds a level that a regulator has defined as "significant". Only when activity concentrations are significant is radiation protection required.

"M" represents not only the mass of material but also can indicate all other non-radioactive components of NORM. These components may be inert or contain chemically toxic substances. Industrial hygiene is about protecting workers from the hazards posed by these substances.

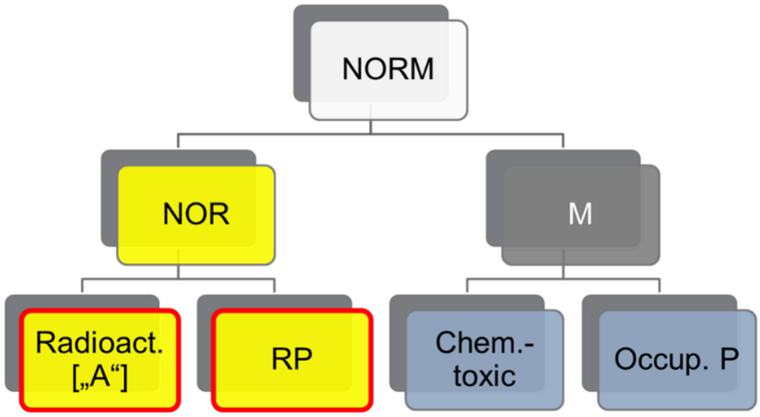


FIGURE 2-3: ILLUSTRATION OF THE TERM NORM.

Explanations see text

In this handbook, we focus on radiation protection in industries involving NORM. Therefore, we use the term 'pragmatically' to refer to any controllable radioactive material containing naturally occurring radionuclides (NOR) that cannot be disregarded from a radiation protection perspective. However, it is important to ensure we do not confuse the two terms (NOR and NORM). While the term NOR can be applied to all naturally occurring radionuclides, including those that are part of the background and typically out of scope of radiation protection, NORM should be used only if NOR occurs in significant amounts.

The main radionuclides in NORM are:

- Decay-series radionuclides of the U-238- and Th-232-series, in some cases also radionuclides from the U-235-series (see Figure 2-4).
- Potassium-40 (K-40).

An important point for practitioners is that soil, rocks, or commodities containing radioactivity **within** or consistent with the regional background level are not considered to be NORM – and, therefore, are not subject to radiation protection. Also, in cases where an authority may want to place controls on areas with naturally elevated radiation levels, e.g., due to radon, this does not make the soil NORM.

Water, plants, food, or feed contain NOR but are usually not considered to be NORM. This holds despite the limited exposure from ingestion, as regulated by law, and the monitoring of drinking water and food activity concentrations by governmental institutions. From a formal point of view, the term NORM can be applied when the limits defined in a law are exceeded, and the radioactivity can be considered significant.

A particular case is water. Liquid discharges from mining sites or industrial plants contain NOR that may form NORM by precipitation or sorption, or directly contribute to public exposure if they are used for irrigation. Therefore, they should be part of our radiation protection tasks.

In this handbook, we will use the term 'NORM' to name solid materials, including sludges, whose radioactivity levels make them a subject of radiation protection. Such NORM is a result of human doings and does not apply to the natural background! (Cf. Section 2.3.9)

An overarching term that can be applied independently of the significance in relation to radiation protection is NOR.

From a practitioner´s point of view, NOR can be grouped into decay series radionuclides and potassium-40 (K-40). In Figure 2-4 the three naturally occurring decay series are depicted. This diagram shows that NOR contains a mixture of radionuclides

- which belong to different chemical elements (rows in Figure 2-4),
- which have very different half-lives (color signatures in Figure 2-4) and
- which have different decay modes (arrows in Figure 2-4).

A table with the half-lives, decay modes, and decay energies of radionuclides is given in the Appendix.

Due to these different properties, individual NOR behave differently in many technical processes. Because of this, you cannot assume that secular radioactive equilibria (typical of geological "old" minerals) are applicable for NORM (see Chapter 3).

AN	CE	U-238-series							Th-232-series					U-235-series				
92	U	238		234										235				
91	Pa	↓	234	↓										↓	231			
90	Th	234		230					232		228			231	↓	227		
89	Ac			↓					↓	228	↓				227	↓		
88	Ra			226					228		224					223		
				↓							↓					↓		
86	Rn			222							220					219		
				↓							↓					↓		
84	Po			218		214		210			216		212			215		
83	Bi			↓	214	↓	210	↓			↓	212	↓			↓	211	
82	Pb			214		210		206			212	↓	208			211	↓	207
81	Tl											208					207	

Figure 2-4: Decay series radionuclides (NOR).

Legend:

AN – Atomic number; CE – chemical element symbol; numbers in cells: mass numbers. ↓ - alpha (α) decay; - beta minus (β-) decay

Colors:

$T_{1/2} > 1000$ a	1 a < $T_{1/2}$ < 100 a	0.01 a < $T_{1/2}$ < 1 a	$T_{1/2}$ < 0.01 a	Stable

2.2.4 How does the radioactive decay law determine the radioactivity of NORM?

Each radioactive decay series starts with a very long-lived primordial mother nuclide and continues with a series of progeny or "decay products", down to a stable lead isotope (see Figure 2-4).

The activity or activity concentration of a radionuclide that is part of a decay series will change with time due to radioactive decay. The radioactive decay law for decay-series radionuclides can be written as

$$\frac{dA_d(t)}{dt} = -\lambda_d \cdot A_d(t) + \lambda_p \cdot A_p(t) \qquad \text{EQU. 2-1}$$

Here, the symbols mean:

$A_p(t)$ activity in Bq (or activity concentration in Bq/kg) of the "parent" or "precursor radionuclide", i.e., the radionuclide that's decay generates the activity A_d

$A_d(t)$ activity in Bq (or activity concentration in Bq/kg) of the decay product ("daughter"), i.e., here the radionuclide whose temporal change shall be calculated.

λ_p Decay constant of radionuclide "p" (precursor or parent)

λ_d Decay constant of radionuclide "d"

The decay constant is related to the half-life according to $\lambda = \frac{\ln(2)}{T_{1/2}}$.

For mathematics on Equ. 2-1, consult the Wikipedia article on the "Bateman equation." An important special case for understanding temporal activity changes in NORM is a long-lived precursor and a short-lived daughter ("Case 2" in the table below). The solution of Equ. 2-1 for this case is

$$\boldsymbol{A_d(t) = A_p(0) \cdot \frac{\lambda_d}{\lambda_d + \lambda_p}\left(e^{-\lambda_p \cdot t} - e^{-\lambda_d \cdot t}\right) + A_d(0) \cdot e^{-\lambda_d \cdot t}} \quad \text{EQU. 2-2}$$

The following four basic cases are essential for understanding the radioactivity of NORM:

Case 1 Radionuclide d occurs alone. There is no precursor. (e.g., due to chemical separation).	**Case 2** The half-life of the precursor (radionuclide p) is much longer than that of its decay product (radionuclide d).
Case 3 The precursor and its decay product have similar half-lives.	**Case 4** A short-lived precursor (radionuclide p) decays and generates a long-lived decay product.

Using radionuclides from Figure 2-5, some examples can be provided. For the calculation, let us assume that the activity of the precursor at the start (t=0) was set to **100 Bq,** and the activity of the decay products at the start (t = 0) was set to zero. It can be seen that:

- **Case 1**: Any isolated radionuclide (for example: Po-210 with $T_{1/2}$ = 138 days) decays completely (to stable lead). (In the case of primordial nuclides, such decay needs longer than the world will exist.)
- **Case 2**: A short-lived decay product (for example: Rn-222 with $T_{1/2}$ = 3.8 days) grows into equilibrium with a much longer-lived precursor (here: Ra-226 with $T_{1/2}$ = 1600 years) **by its own half-life (that is, 3.8 days)**.

  Note 1: Because of this effect, short-lived decay products can be assumed to have nearly the same activity (concentration) as their precursors if the system is undisturbed for more than 5 half-lives[1].

  Note 2: This does not apply if the radionuclides are in continuous technical processes where they decay products behave differently and are separated.

[1] Equilibrium from radon emanation and radon exhalation rates are important to consider for the lower end of the decay series.

- **Case 3**: A decay product with a somewhat lower half-life (for example: Th-228 with $T_{1/2}$ of 1.9 years) than its precursor (here: Ra-228 with T1/2 5.75 years) grows into a running equilibrium (transient equilibrium) with a slightly higher activity than the precursor.
- **Case 4**: A decay product with a much longer half-life (for example: Pb-210 with T1/2 22 years) than its precursor (here: Rn-222 with T1/2 3.8 days) grows up with the half-life of the precursor (!) until its precursor is completely decayed. After this time, it decays as an isolated radionuclide (Case 1).

  This occurs in the smelting and natural gas industries, where these three isotopes behave differently; as a result, one often finds "unsupported" Pb-210 or Po-210.

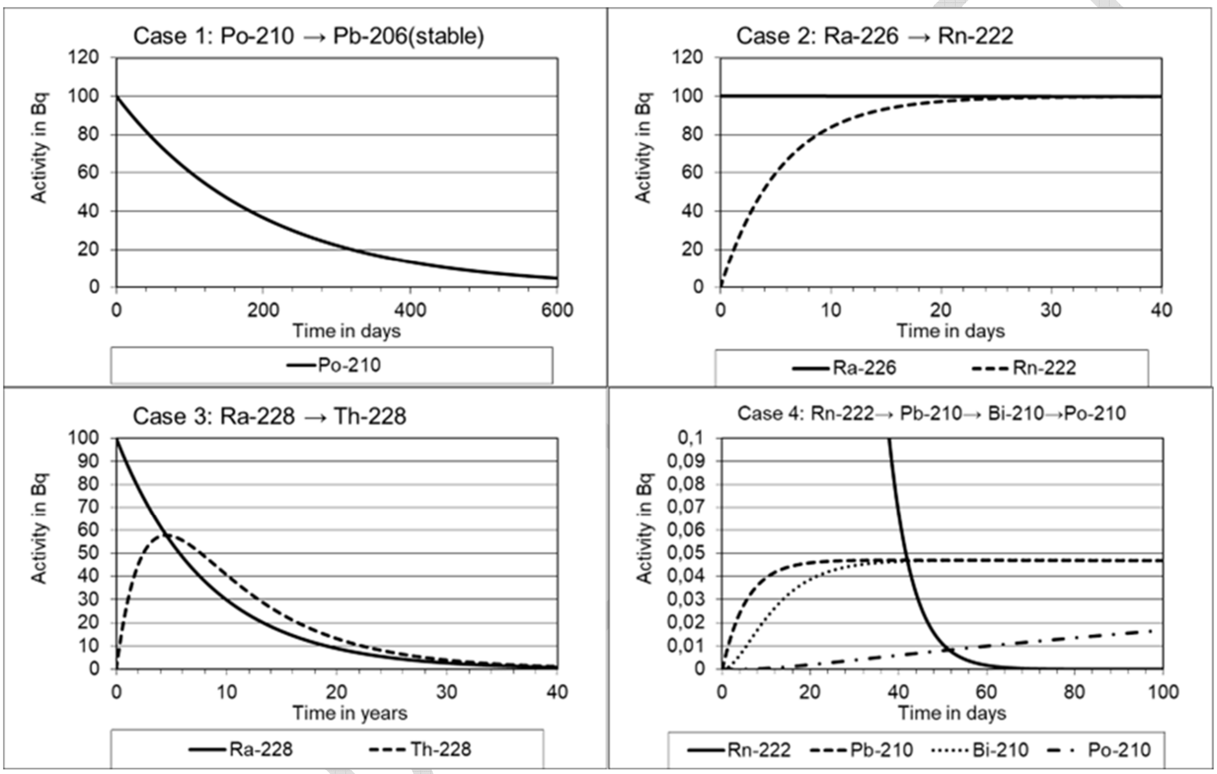


FIGURE 2-5 BASIC CASES OF TEMPORAL CHANGES OF ACTIVITIES IN DECAY SERIES (EXPLANATIONS IN THE TEXT)

The lasting activity (concentrations) reached after longer times (Index "S") in the four cases can be assumed for radiation protection assessments to be:

Case 1 $A_{Po-210,S} \approx 0$ Valid after more than 10 x $T_{1/2}$ of the radionuclide	**Case 2** $A_{Rn-222,S} = A_{Ra-226}$ Valid after more than 5 x $T_{1/2}$ of the decay product
Case 3 $A_d(t) = \frac{\lambda_d}{\lambda_d - \lambda_p} A_p(t)$ Valid after more than 7 x $T_{1/2}$ of the decay product. Note: Both activities are decreasing in time! The activity ratio in the example is $A_{Th-228,S}(t) = 1.49 \cdot A_{Ra-228}(t)$	**Case 4** $A_{2S} = \frac{\lambda_d}{\lambda_p - \lambda_d} A_p(t=0)$ Valid after more than 5 x $T_{1/2}$ of the precursor. Note: The reference is the initial activity A(t=0) of the precursor! The activity in the example is $A_{Pb-210,S} = \frac{1}{2100} A_{Rn-222}(t=0)$

2.2.5 What symbols and abbreviations are used in radionuclide chains?

According to the radioactive decay law, short-lived radionuclides quickly come into an activity equilibrium with their long-lived precursors. To name parent radionuclides and their short-lived progeny, the "+" and "sec" notations are applied. The radionuclide symbol with an added "+" means the radionuclide chain as given in Table 2-3. "Sec" means that the entire decay series is in radioactive equilibrium. Rare branches that do not contribute to doses are neglected.

If operational values like exemption values are given in this notation, contributions of the progeny are considered in the dose calculation.

TABLE 2-3: SYMBOLS OF PARENT NUCLIDES AND INCLUDED PROGENY.

Explanatory notes: Numbers in brackets are the branch ratio. The time to establish equilibrium is estimated as 5 half-lives of the longest-lived progeny.

Symbol	Included progeny	Time for establishing equilibrium
Pb-210+	Bi-210, Po-210	1.9 years
Pb-212+	Bi-212+	5 hours
Bi-212+	Tl-208 (0.36), Po-212 (0.64)	15 minutes
Rn-220+	Po-216	1 second
Rn-222+	Po-218, Pb-214, Bi-214, Po-214	3 hours
Ra-223+	Rn-219, Po-215, Pb-211, Bi-211, Tl-207	3 hours
Ra-224+	Rn-220, Po-216, Pb-212, Bi-212+	2.2 days
Ra-226+	Rn-222+, Pb-210+	110 years
Ra-228+	Ac-228	30 hours
Ac-227+	Th-227, Ra-223+	4 months
Th-228+	Ra-224, Rn-220, Po-216, Pb-212, Bi-212+	20 days
Th-232sec	Ra-228+, Th-228+	30 years
Th-234+	Pa-234m	6 minutes
U-235+	Th-231	5 days
U-235sec	U-235+, Pa-231, Ac-227+	160,000 years
U-238+	Th-234, Pa-234m	4 months
U-238sec	U-238+; U-234, Th-230, Ra-226+	1.3 Mio. Years

2.2.6 How does chemistry influence radioactive elements?

Aqueous solution processing of materials containing NOR is a typical treatment method in industries involving NORM. Knowing some basics about the chemical properties of radionuclides helps understand where they can potentially accumulate as NORM in the industry, forming a radiation source that must be considered for RP reasons. Moreover, the different chemical properties of radionuclides belonging to different chemical elements usually result in activity disequilibria among members of the same series.

Two basic parameters that rule the mobility of NOR in aqueous solutions are pH and Eh.

- pH affects the ionization (charge state) of the substance and of the solvent environment. Therefore, the solubility of many substances increases at low (acidic) or very high (alkaline) pH values.
- Eh (also called redox potential or oxidation–reduction potential) controls the oxidation state of elements in solution or in solids. Different oxidation states of a chemical element often have very different solubilities. Eh only affects chemical elements with different valencies, which may occur in various oxidation states. Uranium is such an element (main valencies +VI, *+IV). Because the only valency of radium is +II, its solubility is not directly affected by the Eh. However, because in a reducing environment (low Eh), sulfate ions are reduced to sulfites, the solubility of radium depends indirectly on the redox milieu.

Table 2-4 summarizes chemical conditions that promote or prevent NOR leachability in aqueous solutions, both natural and industrial. Please note that in all NORM-related processes, only uranium, thorium, lead, and potassium may occur in mass concentrations (µg/l) that are sufficient for limiting the solubility of compounds. The chemical behavior of lead and potassium results from their stable isotopes. The radionuclides Pb-210 and K-40 are not decisive for the chemical behavior.

The amount of substance (mol) of radium, polonium, actinium, and protactinium is too small to limit the solubility of their salts in industrial process solutions. Therefore, the chemical behavior of the radionuclides Ra-226, Ra-228, Po-210, Ac-227, and Pa-231 in aqueous solutions is dominated by elements with similar chemical properties, like barium (for radium), tellurium (for polonium), and lanthanum (for actinium).

The periodic table tells us that elements in the same group behave similarly due to their chemical properties. An understanding of these groups also helps the practitioner understand where radionuclides may accumulate. Some chemical similarities derived from the periodic table are summarized in Table 2-5.

Another aspect in which the chemical properties of the NOR affect radiation protection is biokinetics. Biokinetics determines the distribution of radionuclides in organs and tissues, as well as the residence time the radionuclides remain in the body. Therefore, the dose coefficients for inhalation depend on the chemical form of inhaled radionuclides. A summary of chemical forms and inhalation absorption classes is given in the Appendix.

As previously noted in this handbook, a further essential aspect of chemistry is that NORM can contain chemically toxic substances in addition to its radioactivity. This handbook focuses on radiological aspects. While radioactivity, including that of NORM, is a known human carcinogen, impacts to workers, the public, and non-human biota should consider all hazards and risks using an integrated approach (see Chapter 4).

TABLE 2-4: CHEMICAL CONDITIONS PROMOTING OR PREVENTING NOR LEACHABILITY IN AQUEOUS SOLUTIONS

	Preferred oxidation state	Conditions promoting solubility in aqueous solutions	Conditions resulting in low solubility in aqueous solutions
Uranium	+IV +VI (+V; +III)	Oxidizing conditions (6+ as uranyl-ion $(UO_2)^{2+}$). Most acidic or alkaline solutions, in particular as uranyl carbonate, chloride, or sulfate.	Reducing conditions (4+) Under oxidizing conditions, sorption onto Fe(III) oxyhydroxides. Uranyl phosphate
Thorium	IV	Main mobile species are hydroxides in a high pH range. High dissolved carbonate concentration promotes solubility.	Generally immobile at neutral pH; not sensitive to Eh changes since it only occurs as +IV. Oxides and hydroxides are the main mineral precipitates.
Radium	II	Quite soluble in all kinds of fluids, especially in very saline fluids, in which $RaCl^+$ aqueous species are more relevant. Not affected by Eh changes.	The occurrence of minor amounts of barium and sulfate promotes barite precipitation, which co-precipitates radium. Cation exchange reactions in clay minerals.
Lead	II IV	Commonly found as Pb(II); under circumneutral conditions, cationic aqueous complexes are dominant. At alkaline pHs, Pb forms anionic complexes.	Low solubility of sulfides and carbonates, but keep in mind that lead radioisotopes by themselves are too low in concentration to form their own minerals. Cationic aqueous species can be involved in sorption or mineral co-precipitation (i.e., hokutolite -lead-bearing barite).
Polonium	-II +II +IV	Affected by Eh changes since it has multiple oxidation states. At alkaline conditions, HPo^- aqueous species promotes mobility.	Po (II)species are prone to adsorption onto mineral surfaces.
Actinium	+III	Experimental data are rare. Soluble in seawater [9], [10]. Transferred from lanthanum: Soluble in hydrochloric, sulfuric, and nitric acid solutions [11].	Insoluble as carbonate or phosphate [11]. Co-precipitation in carbonate minerals like calcite.
Protactinium	+IV +V	Experimental data are rare.	Scavenged by particles in seawater. [10]
Potassium	+I	Very soluble in aqueous solutions	

TABLE 2-5: CHEMICAL SIMILARITIES WITH OTHER ELEMENTS

Uranium	Molybdenum (Mo) and Tungsten (W) (group 6); Vanadium (V) (group 5), Chromium (Cr, especially Cr(VI)) behaves somewhat like uranyl ion
Thorium	Hafnium, Zirconium, Titanium, (partly Protactinium)
Radium	Barium, Strontium, Calcium, (less similar: Magnesium) Earth alkali group
Actinium	Lanthanum (and other elements of the Lanthanum Group), Yttrium, Scandium
Lead	Tin, Bismuth, Thallium
Polonium	Tellurium, Selenium
Potassium	Sodium, Rubidium, Cesium (Alkali group)

2.2.7 How does temperature affect radioactive elements?

At high temperatures, the physical form of some chemical elements changes. This may lead to elements being released from solids or molten ores as vapors. This effect starts at temperatures above the element's melting point, increases with increasing vapor pressure, and becomes complete once the element's boiling point is exceeded.

This is an important consideration in practical radiation protection.

As has been noted, radionuclides occur as chemical compounds (Po, Ac, Pa) or minerals. These minerals may behave differently from elemental forms. Because they are distributed as traces in a matrix, they decompose at high temperatures into their chemical constituents. Up to this point, they remain solid and do not or only slightly evaporate.

In Figure 2-6 the melting and boiling temperatures of the radioactive elements, as well as their common mineral forms or compounds, are depicted in a diagram. For comparison, the temperatures in blast furnaces for pig-iron production and in melting furnaces for non-ferrous ores are also displayed.

This diagram shows that potassium and polonium evaporate at temperatures below 1000°C. Actinium, protactinium, thorium, and uranium do not evaporate at the temperatures applied in common technical processes.

The boiling temperatures of lead and radium are in the range where melting processes operate. Although the boiling points of Pb and Ra are nearly the same, Pb-210 evaporates in a blast furnace process at 1500°C to a significant amount, but Ra-226 remains in the slag (cf. Chapter 3). The reason for this effect is the mineral form. For lead, the typical form, PbS, decomposes at 1050°C, releasing lead atoms that can evaporate. The typical form that Ra occurs is Ba(Ra)SO4 (keeping in mind that radium sulfate does not exist in nature as a separate form from the solid solution). $BaSO_4$ decomposes at 1560°C, i.e., 500°C higher than PbS, and consequently, radium remains covered in a solid form up to much higher temperatures than lead. However, in electric-furnace sintering processes at temperatures exceeding 1700°C, radium begins to evaporate and concentrate in filter dust.

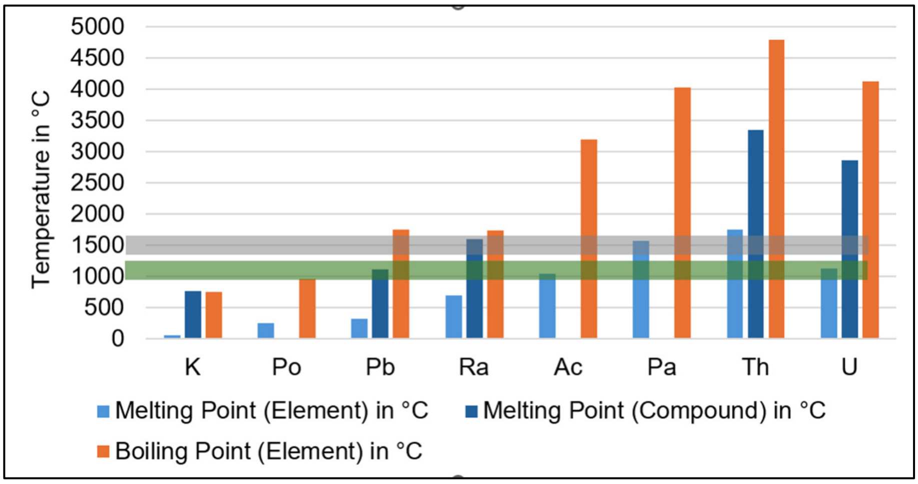


FIGURE 2-6: MELTING AND BOILING POINTS OF RADIOACTIVE ELEMENTS.

Note: The lower bar shows the temperature range of non-ferrous metals melting; the upper bar shows the same for pig-iron.

Because of its noble gas character, radon partitions according to its own rules, depending on temperature. At high temperatures, it escapes from solids and nearly completely from liquids (including molten metals). At low temperatures, the solubility in water or other liquids increases. This effect results in preferential partitioning of radon with ethane and propane during cryogenic processing. We cover radon in more detail in the Section 2.4.

2.2.8 How to characterize the composition of NORM?

When assessing NORM for radiation protection, both the nuclide composition and the activity concentrations are required. This is because the radiation risks associated with various radionuclides differ.

As described in the preceding sections, the radionuclide composition in NORM can be highly complex. For most practical cases, short-lived radionuclides with half-lives less than 10 days can be assumed to have the same activity concentration as their long-lived precursors. One important exception is radon because of its noble gas characteristics (this is covered in later Sections). Therefore, the following long-lived radionuclides are sufficient for characterizing NORM:

- Th-232-series: Th-232, Ra-228, Th-228
- U-238-series: U-238, (U-234), Th-230, Ra-226, Pb-210, Po-210;
- In specific cases, Pa-231 and Ac-227 from the U-235-series can be relevant, too.

U-235 does not need to be characterized because it occurs in a very constant activity ratio of 0.046 to U-238.

U-234 activity concentration can usually be assumed to be equal to that of U-238.

Po-210 is frequently in equilibrium with Pb-210; however, it may dominate the radioactivity of filter dust in processes with temperatures in the range 900-1100°C (see Section 3.9).

A method to characterize the composition of NORM is shown below and is based on assumptions about radionuclide concentrations. It represents a standardized approach based on measured activity concentrations, as follows:

$$C_{iN} = \frac{c_i}{c_{Th232max} + c_{U238max}} \qquad \text{EQU. 2-3}$$

Where

C_{iN} is the standardized activity concentration of radionuclide "i".

C_i is the (measured) activity concentration of radionuclide "i".

$C_{Th232max}$ is the highest individual activity concentration (measured) in the Th-232-series.

$C_{U238max}$ is the highest individual activity concentration (measured) in the U-238-series.

This approach is simple and robust. It can be applied if the radionuclides with the highest activity concentrations in the U-238 and Th-232 decay series have been determined. The standardization can also be used for Pa-231 and Ac-227. However, for the U-235 radionuclides, remember that the activity concentrations of both radionuclides have to be multiplied by the activity ratio U-238/U-235 of 22 (rounded: 20).

This method produces standardized patterns of radionuclide compositions, which are helpful for the following reasons:

- They make it possible to identify NORM with a similar composition and determine characteristic compositions of different **NORM types**.
- They allow for assessing the effect of technical processes on the nuclide composition of NORM.
- They can be used to **check the plausibility** of analytical results.
- Such patterns can be used to make an **indirect determination** of radionuclide levels, i.e., measuring results can be supplemented appropriately with concentrations of radionuclides not measured and thus make a more realistic assessment of exposures (see Chapter 5).

Related to typical processes in industries involving NORM, the NOR-patterns of six basic types of NORM are depicted in Figure 2-7. The diagrams in Figure 2-7 are examples only and will differ in detail in each individual case. However, the following characteristic patterns remain the same:

- **Type M1: Minerals and ores** of geological origin. Geochemical processes occur over geological timeframes, and the age of the materials is usually several million to hundreds of millions of years. Therefore, it is reasonable to assume that each decay series in the raw materials is in equilibrium, i.e., all radionuclides of the same decay series have the same (normalized) activity concentration.

  Note 1: Where groundwater is intensively flowing, the equilibrium can be disturbed.

  Note 2: In very special cases, geologically "young" materials can be raw materials, too. Examples are geologically young peat deposits, precipitates in active geothermal systems, and manganese nodules found in deep-sea areas [12].

- **Type M2: Digestion residues.** Hydrometallurgical processes use acidic or alkaline solutions (called reagents) to digest minerals. Depending on the type of reagent, the remaining solids (tailings) may typically be depleted in specific radionuclides. i.e., their normalized activity concentration is lower than the activity concentration of radio-nuclides that are less soluble in the agent. However, in these cases, the radionuclides must be dissolved in the reagent. Particular examples are given in Chapter 3.

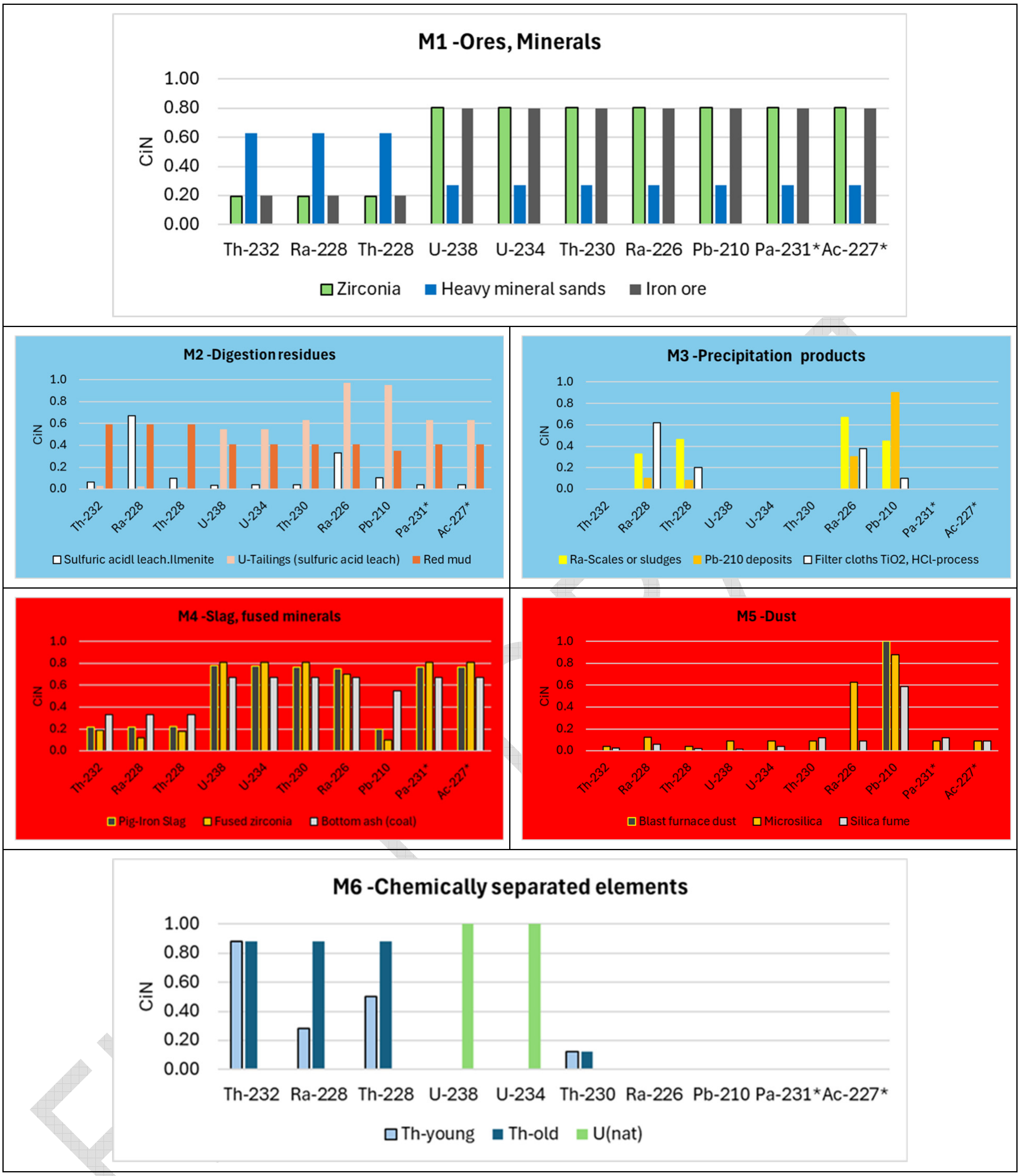


FIGURE 2-7: ***EXEMPLARY DIAGRAMS OF NORMALIZED RADIONUCLIDE COMPOSITIONS OF SIX BASIC NORM-TYPES. EXPLANATIONS SEE TEXT.***

Note: Blue: aqueous solution processes. Red: High-temperature processes)

- **Type M3: Precipitation products** are insoluble compounds (salts) typically generated by chemical reactions in aqueous solutions. Radionuclides may be incorporated in such salts and co-precipitated. Typical processes are the co-precipitation of radium in earth alkali sulfates, such as (radio)barite ($BaRaSO_4$), which is thermodynamically favored over pure barite and is frequently found as scales and sludges in oil or gas production facilities. Another example is filtered particles from the chloride digestion of TiO_2

production, which also capture radium by co-precipitation. Commonly, Ra-226 or Ra-228 dominates the activity concentrations in such precipitation products.

Note 1: Other chemical reactions will result in other radionuclide patterns in precipitation products. e.g., uranium is precipitated with phosphate.

Note 2: A particular precipitation product, Pb-210, from the decay of Rn-222 in natural gas, results in surface contaminations of pipelines.

Note 3: Sorption at iron(III) oxyhydroxides may result in similar radionuclide patterns as co-precipitation.

- **Type M4: Slags** (e.g., blast furnace slags) or **fused minerals** (e.g., Zirconia) generated at high temperatures are typically depleted in Pb-210.
- **Type M5: Dust** from pyrometallurgy or other high-temperature treatments is a minor mass stream generated during melting, sintering, or fusing. It contains elements that evaporate at the process temperatures occurring (see Section 2.2.7).
- **Type M6** stands for **Products with chemically separated radioactive elements.** Such products contain natural thorium, natural uranium, or radium (Ra-226) in chemically pure forms or as trace components. Well-known are thoriated tungsten electrodes. But, for example, dicalcium phosphate, an additive used in the poultry industry, typically contains uranium from phosphate ore that has passed through many steps of the production chain. For the same reason, phosphate fertilizers may contain chemically separated uranium.

More on the application of normalized NORM composition is given in Chapters 3 and 5.

2.2.9 How can you get additional information?

Basic data on the properties of uranium, radium, and polonium can be found in:

- IAEA TRS476 "The Environmental Behaviour of Radium: Revised Edition"
- IAEA TRS488 "The Environmental Behaviour of Uranium"
- IAEA TRS484 "The Environmental Behaviour of Polonium"

Core textbooks on radioactivity are available in different languages. Some textbooks in English are

M. Eisenbud, Th. Gesell: Environmental Radioactivity: From Natural, Industrial, and Military Sources [13]

Level: Upper Undergraduate / Graduate. **Focus:** Classic and still the most widely adopted general textbook in environmental radioactivity. Covers natural background, fallout, waste disposal, and dose estimation. Strong historical and regulatory context.

M. Ivanovich and R.S. Harmon: Uranium-series disequilibrium: applications to earth, marine, and environmental sciences [14]

Level: Upper Undergraduate / Graduate. **Focus:** Geochemistry of actinides and their daughters; chemical procedures and spectroscopic methods. Uranium-series disequilibria applications in geochronology and environmental sciences.

Textbooks in French on the basics are:

D. Delacroix: Guide pratique Radionucléides & Radioprotection [15]

This book is widely used because it contains fact sheets on the most commonly encountered radionuclides, including their nuclear characteristics and associated radiation protection.

R. Antoni, L. Bourgois : Physique appliquée à l'exposition externe - Dosimétrie et Radioprotection [16]; R. Antoni, L. Bourgois : Résolutions de problèmes sur les rayonnements ionisants - Dosimétrie, instrumentation, protection radiologique [17]

Keywords for these two books are: dosimetry, detection of ionizing radiation, measurements, calculation of doses from external exposure, dosimetric quantities, interaction of radiation with matter, operational dosimetry, and principles and use of Monte Carlo methods.

R. des Bois : La Radioactivité Naturelle Technologiquement Renforcée [18]

Keywords are: TNORM, natural radionuclides in materials or waste from industrial processes, and relevant industrial sectors.

Freeware software for simple dose calculations

> **Rad Pro Calculator:** Free Online dose rate calculations. Radiological units conversions: http://www.radprocalculator.com/
> **Wise U calculators:** https://www.wise-uranium.org/calc.html
> https://www.wise-uranium.org/rdcrn.html

Maps for Europe with data on uranium, thorium, and potassium in soil, as well as data on cosmic ray doses and radon, are published in **The European Atlas of Natural Radiation** [19].

2.3 How to protect against radiation risks from NORM?

2.3.1 Where is radiation protection not needed? (Exclusion, exemption, clearance)

In most countries, radiation protection is based on the recommendations of the International Commission on Radiological Protection (ICRP) and the standards derived from these recommendations by the International Atomic Energy Agency (IAEA).

Generally, the radiation protection system (for ionizing radiation) aims to protect people and the environment against the detrimental effects of radiation exposure without unduly limiting the desirable human actions associated with such exposure (ICRP 103 [20] para 26). To implement this aim in a practicable manner, it is necessary to ensure that the radiation protection system is not applied in areas that do not need radiation protection. This demarcation is made by the terms "exclusion" and "exemption".

The term **exclusion** describes the fact that some radiation sources and exposures are not amenable to control and are therefore excluded from the requirements for radiological protection legislation. Exclusion is typically implemented within the scope of legislative systems by defining what is not regulated. Typical exposures that are not amenable to control include exposure from K–40 in the human body, from cosmic radiation at the Earth's surface, and from unmodified concentrations of radionuclides in most raw materials (cf. IAEA Glossary [4]). This also applies to natural background radiation, unless otherwise required by the regulatory authority.

As a consequence of excluding uncontrollable radiation, radiation protection focuses on incremental doses above background radiation.

Exposures that do not need to be regulated are **exempted** from some or all radiological protection regulatory requirements. This is the case if controls are regarded as unwarranted, often because the effort to control is considered inappropriate compared to the associated risk (ICRP 103 [20] para 52).

Unlike exclusion, which makes very general qualitative statements, exemption depends on quantitative values of the effective dose, the activity, or the activity concentration of radionuclides. While the effective dose (which cannot be measured directly) always refers to radiation from controllable sources (i.e., without background radiation), activity or specific activity is a quantity that can be directly measured for materials. Depending on the material´s origin, its measured activity concentration may characterize the natural background or a controllable source.

There is also a third category of material for which the radiation protection system does not apply: materials that have been within the control system and then “cleared” from it. The term **clearance** describes the situation where materials under regulatory control with sufficiently low levels of radioactivity no longer need to be regulated. In such a case, radioactive materials may be released from the authority's control. The prerequisite for the release is a permit from the radiation protection authority.

In everyday communication, however, the terms exclusion, exemption, and clearance are often used interchangeably. As practitioners, it is important to ensure that the basic concepts are understood, as the requirements for each differ.

A summary of the application of exclusion, exemption, and clearance is given in Table 2-6.

TABLE 2-6: EXCLUSION, EXEMPTION, CLEARANCE

	Activity concentration	**Comment**
Exclusion	Non (independent from activity concentrations)	Regulated within the scope of laws. No specific evidence required. A decision based on it is not amenable to control.
Exemption (NORM)	Typically*: 1 Bq/g for each decay series radionuclides and 10 Bq/g for K-40 (national values may differ!)	Regulated in national law. Proof of compliance may be required.
Clearance	Usually, generic clearance values are the same as the exemption values. Supplementary, specific (higher) clearance values based on dose estimates (e.g. 1 mSv per year effective dose) can be applied in specific cases.	Requires approval by the authority.

* The 1 Bq/g values are based on the worldwide variation of uranium and thorium concentrations in soil, not on dose estimates.

Any material that is not excluded or exempted can be radioactive material. ICRP 103 [20] and the IAEA Glossary [4] define the term radioactive material as a material designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity. Any radiation that is not excluded and is caused by radionuclides that are not exempted must be considered “significant” in a regulatory context. However, the national approaches to the legal definition of a radioactive material (i.e., a material subject to regulation) differ considerably, particularly in the field of NORM. Some examples of national regulatory approaches are described in Chapter 4 and Chapter 7. Examples of different national exemption values for determining "significance" are given in Table 2-8. An example that demonstrates the challenges to apply the terms exclusion and exemption in specific cases is given in Section 2.3.9.

Moderate amounts

In IAEA's GSR Part 3 [5], the IAEA defines two criteria for the exemption of material containing radionuclides. The first criterion is radionuclide concentration, and the second is total radionuclide activity. If one of the criteria is exceeded, then the material is classified as radioactive. However, in the case of NORM, the activity concentration is the only criterion. This approach is justified with the assumption that in industries involving NORM, only bulk amounts of NORM exist. Consequently, even small quantities of NORM with activity concentrations above the exemption criteria of 1 kBq/kg for each decay-series radionuclide must be classified as "radioactive".

The dose to which a person may be exposed depends much more on the total activity than on activity concentration. Therefore, doses exceeding 1 mSv/y are unrealistic if small or moderate amounts of NORM (less than 1 ton (Mg) or only a few tons) are handled once a year. However, when considering the total activity criteria for "moderate amounts" in IAEA GSR Part 3 [5], only a few kilograms of material are required to be classified as radioactive. For example, a material containing 1 kBq/kg of Ra-226 (and decay products in equilibrium) exceeds the exemption value of 1E+04 Bq when the mass exceeds 10 kg. This is despite the very low potential radiological risk. At a practical level, this creates unnecessary concern.

2.3.2 Why is radiation protection needed for NORM?

NORM, as it occurs in mining or industry, is a mixture of different chemical substances and radionuclides. Therefore, it can present both radiological and chemical hazards (see Figure 2-3).

Radionuclides emit ionizing radiation, which consists of quantum particles having enough energy to remove tightly bound electrons from atoms, potentially damaging or destroying cellular structures. This can lead to mutations in DNA, which may result in cancer or other serious health issues. This statement applies to all types of ionizing radiation, regardless of its origin (natural, artificial, or cosmic). Consequently, radioactivity, including that from NORM, is known to be a human carcinogen.

The chance of a radiation-induced cancer has been regularly determined from many epidemiological studies. UNSCEAR reviews the studies and provides a risk factor for excess cancer risk per unit effective dose, and this is 5% per Sievert [21]. In its publication 103, ICRP has confirmed this factor as a basis for risk assessments [20]. UNSCEAR also notes that this factor is based on the linear no-threshold theory (LNT), which says that any exposure increases cancer risk. This is even though there is no evidence of impacts at low doses, such as the doses that typically would be seen in operations with NORM.

Because we live in a world full of ionizing radiation from naturally occurring radionuclides and from cosmic radiation (see Box 2-1). According to UNSCEAR 2024 [22], the worldwide annual effective dose from natural sources ranges from 1 to 14 mSv, with an average of about 3.0 mSv. The main contributor is radon (Rn-222 and Rn-220), accounting for 1.8 mSv.

Consequently, it is impossible to avoid radiation completely, and doing so would probably be unhealthy.

> **BOX 2-1: SOURCES AND CHARACTERISTICS OF BACKGROUND RADIATION**
>
> UNSCEAR 2024 [#] gives the population-weighted worldwide average of natural radiation as:
>
> **Cosmic radiation**: 37 nGy/h at sea level. (up to 1 km altitude). Average annual dose: 0.3 mSv.
>
> **Terrestrial Radiation:** Dose rate outdoor 49 nGy/h based on activity concentrations in soil U-238 30 Bq/kg; Ra-225: 33 Bq/kg; Th-232: 42 Bq/kg; K-40: 512 Bq/kg. Average annual dose including indoor exposure: 0.4 mSv.
>
> **Ingestion exposure:** 0.25 mSv per year age-weighted annual dose from radionuclides other than K-40 (52% Po-210; 16% Pb-210; 24% Ra-228; 4 % Ra-226; other: 4%). Total food and water, including K-40: 0.5 mSv.
>
> **Inhalation exposure** by dust/aerosols: 0.006 mSv per year age-weighted annual dose based on activity concentrations 500 µBq/m^3 for Pb-210, 50 µBq/m^3 for Po-210; 1 µBq/m^3 for U-238, Ra-226, Ra-228, and Th-228; 0.5 µBq/m^3 for Th-232 and Th-230.
>
> **Radon gas (Rn-222)**: Reference values: Indoor: 50 Bq/m^3; outdoor: 10 Bq/m^3. Annual dose 1.4 mSv (Dose coefficient 9 nSv/h per Bq/m^3; F_{indoor} 0.4; $F_{outdoor}$ 0.6).
>
> **Thoron gas (Rn-220)**: $EEC_{Rn\text{-}220}$ of 1.2 Bq/m^3 indoor and 0.3 Bq/m^3 outdoor. Annual dose (rounded) 0.4 mSv (Dose coefficient for EEC of thoron 40 nSv/h per Bq/m^3).
>
> **Worldwide average effective dose: 3.0 mSv/y**

However, there is no scientific evidence that exposures in the normal environmental ranges cause cancer. In its Publication 103 paragraph 66 *[20]*, the ICRP "*emphasizes that whilst the LNT model*[2] *remains a scientifically plausible element in its practical system of radiological protection, biological/ epidemiological information that would unambiguously verify the hypothesis that underpins the model is unlikely to be forthcoming. Because of this uncertainty on health effects at low doses, the Commission judges that it is not appropriate, for the purposes of public health planning, to calculate the hypothetical number of cases of cancer or heritable disease that might be associated with very small radiation doses received by large numbers of people over very long periods of time.*"

The second part of this ICRP statement is very important for practitioners. We are usually not experts in the fields of radiation biology or epidemiology, and therefore, we should be very careful about our statements on the carcinogenicity of radiation. This is particularly important because the fear and stigma associated with radiation can lead to bad decisions, wasted resources, psychological distress, and anxiety, impacting mental health. **Radiation is to be respected, not feared.**

Radiation protection in industries involving NORM aims to prevent chronic exposure to radiation beyond general background radiation or to reduce it to such an extent that the theoretically resulting risks remain tolerable. In these cases, we can say that the exposure and protection situation has been optimized. As noted above, the need for radiation protection against risks from low doses of natural origin is not based on direct evidence of cancer. Instead, it is "*the best practical approach to managing risk from radiation exposure and commensurate with the 'precautionary principle' (UNESCO, 2005)*." [20] On the other hand, there is also no scientific evidence that low doses are not harmful. This is the prudence part of the ethics of radiation safety.

[Note that this is not the case for exposure to naturally occurring radon, which is the leading natural cause of lung cancer in the world.]

[2] A dose-response model which is based on the assumption that, in the low dose range, radiation doses greater than zero will increase the risk of excess cancer and/or heritable disease in a simple proportionate manner. (From ICRP 103)

International institutions have noted that balancing the LNT, the precautionary principle, and the very low risk at low doses is difficult, and that this usually falls to the practitioner. ICRP noted that "*this creates some difficulties in explaining the control of radiation risks.*" ([20 Para. 38) However, as professionals in radiation protection, we should know that the precautionary principle is also a widely used approach in environmental and occupational protection and is also applied in the context of other non-threshold carcinogens. Moreover, our whole regulatory system for radiation protection is based on that principle.

With NORM, we are not involved with emergency situations, where there is a risk of deterministic doses and where any mistake may result in fatalities. However, our actions are important because they continue to ensure the well-being and safety of workers, the public, and the environment, even in lower-level exposures, where we base decisions on optimizing risk and benefit and on the precautionary principle. This is indeed a core function of a modern safety culture, which includes a holistic (see Chapter 9) and graded (see Chapter 4) approach to radiation safety programs.

2.3.3 How is the RP system for NORM built?

Our current radiation protection system is complex and has been developed over time as new challenges emerge and new information becomes available. There is no doubt that it is a comprehensive system, and our task as practitioners is to put the system into practice either as legislation or by implementing legislation.

One way of thinking about the system is as a framework or a structure with many components (see Figure 2-8). The foundation of the system consists of the three key principles: justification, optimization, and limitation, which underlie our approach to radiation protection. To consider the entire range of exposure in a structured manner, the ICRP has developed three types of exposure situations and three categories of exposure. Recently, there has been discussion about an additional category of exposure for non-human species (plants and animals). For each group of persons (or species) covered by the exposure categories, dose criteria are established. This whole system forms the basis of the International Standards established collaboratively by the IAEA, which then are adopted in National laws.

As practitioners we assess individual situations or cases, initiate appropriate actions and advise on the management of the exposure to ensure compliance with the requirements. To do this requires detailed knowledge of the concepts and meanings of the terms that are given in Figure 2-8. Therefore, in the rest of this section, these terms are briefly explained with special consideration of their role in the RP for NORM. More detailed descriptions on how the RP can be planned, organized and managed are contained in the further chapters of this handbook.

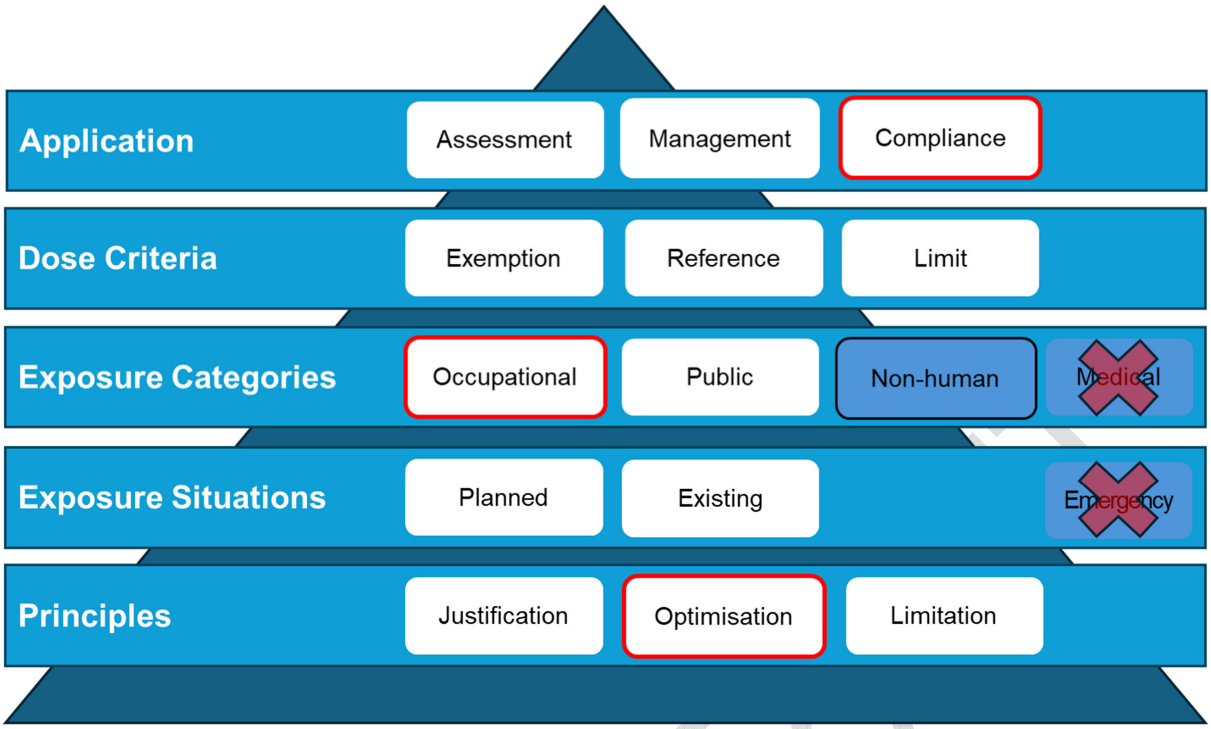


FIGURE 2-8: RADIATION PROTECTION SYSTEM WITH KEYWORDS RELEVANT FOR NORM BASED ON THE 2007 RECOMMENDATIONS OF ICRP

Note: For this handbook on NORM, we have excluded emergency exposure situations and medical exposure categories.

Foundation level / Principles

The key Principle of Justification was initially intended for assessing whether a planned activity involving radiation is, overall, beneficial, *i.e. whether the benefits to individuals and to society from introducing or continuing the activity outweigh the harm resulting from the activity* (ICRP 103). This kind of justification is not usually applicable to NORM. The radioactivity of NORM in mining or industry is a hazard and risk that can be managed as part of the overall health and safety system. For that reason, the **Principle of Justification for NORM means asking whether the benefits to individuals and society from introducing or continuing a radiation protection action outweigh its costs and any harm or damage it causes.** As previously noted, in many cases, other risks, especially risks from chemically toxic substances, must also be taken into account. Therefore, a decision on justification should be reached through a communication process involving all stakeholders, considering all aspects.

At the level of operational radiation protection, the **Principle of Optimization of Protection** is much more important. In practice, it means that we have to keep the likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses **as low as reasonably achievable,** taking into account economic and societal factors. To do this in practice is a challenge. However, we can draw on several instruments for this purpose. One is to follow the Graded Approach (GA) and *to establish a system of control, in which the stringency of the control measures and conditions to be applied is commensurate, to the extent practicable, with the likelihood and possible consequences of, and the level of risk associated with, a loss of control* [4]. Some aspects of this GA are summarized in Chapter 4. Another is learning from others and their experience, as summarized throughout this document and in Chapter 6 in particular, and also in Chapter 9.

Another very practical instrument is the "risk assessment", which is used for other risks and hazards in industry. The risk assessment considers what could go wrong and then applies control or mitigation measures until the risk is deemed acceptable.

It is important to understand that optimization is not a task that can be forgotten once completed. It is an ongoing process, very similar to the concept of continuous improvement.

The third and final key principle of radiation protection is the Principle of Application of Dose Limits. This principle means that the total dose to any individual from regulated sources, in our case NORM, in planned exposure situations, should not exceed the appropriate limits specified by the national authority. The details of this principle will be discussed later in this handbook under the topic "Dose Criteria".

Level 1: Exposure situations

Radioactivity that cannot be disregarded from a radiation protection perspective occurs in many forms and situations. To structure the RP system and to cover the entire range of exposure situations, ICRP [20] has introduced the three types of exposure situations, outlined in Figure 2-8.

NORM rarely poses an "emergency situation," as described by ICRP, since concentrations and exposures do not pose acute radiation hazards. Therefore, emergency exposure situations do not play a role in radiation protection with NORM and are consequently removed in Figure 2-8[3].

The remaining planned and existing exposure situations relate to different regulatory approaches. A summary of both concepts is given in Table 2-7.

TABLE 2-7: COMPARISON OF PLANNED AND EXISTING EXPOSURE SITUATIONS (ICRP 103).

Planned exposure situations	**Existing exposure situations**
Situations involving the planned introduction and operation of controllable sources	Situations that already exist when a decision on control must be taken, including natural background radiation and residues from past practices that were operated outside the ICRP recommendations.
The level and range of exposure can be estimated in advance and influenced by protective measures planned based on the estimation.	Exposure has already occurred at the time, but estimation of doses or determination of activity concentrations is necessary for decision on control.
Regulations contain **dose limits**; i.e. values not allowed to exceed within the planned actions.	Regulations refer to **reference values**, which are the values used for deciding on the requirements of control and optimization. Exceedance requires actions.

In its Publication 103 [20], ICRP has considered NORM and radon as examples of existing exposure situations. However, in Publication 142 [23], the ICRP has considered NORM in greater detail and modified its initial view.

[3] While not generating tissue effects by ionizing radiation, skin burning by UV-radiation may be an issue in industries involving NORM.

There is a consensus amongst institutions that for industries that process NORM, such processes can be considered analogous to the planned use of radioactive sources. Therefore, (for example, the EU in its Directive 2013/59/Euratom), for radiation protection in industries with NORM, they are considered a planned exposure situation, with occupational radiation exposure management for workers (for example, in IAEA GSR 3 [5]).

When considering the radiological risks, there is also recognition that other hazards and risks should be considered to ensure a more integrated approach (see Chapter 4) to health and safety. While a central objective of ICRP Publication 103 is to recommend a uniform and standard approach to the management of all types of exposure situations, for industries with NORM, it remains important to ensure that an integrated "all hazards" approach is adopted.

Industries with NORM are generally significant contributors to the economy. They are large, employ many people, and face numerous hazards and risks. Ensuring the balance between radiological impacts and the costs of controls and regulations is important. In practice, a graded approach based on the level of risk and other considerations, such as economic and social factors, is crucial.

Level 2: Exposure categories

The ICRP identifies three categories: occupational, public and medical exposure. Meanwhile, the exposure of non-human species is considered to be a fourth category (see Figure 2-8).

Note that for this handbook on NORM, the reference to medical exposures is not considered.

The key part of radiation protection in industries involving NORM is the protection of workers. In practice, the ICRP restricts the use of the term "**occupational exposure**" to radiation exposures at work that are attributable to situations that "*can reasonably be considered to be the responsibility of the management*".

A special case is the exposure of the embryo and fetus of pregnant workers. This fetus is considered to be a member of the public[4].

Public exposure encompasses all exposures of members of the public from the activities of the particular facility. The exposure may result from discharges from mines or industrial facilities, the uncontrolled accessibility to contaminated legacies, the controlled disposal of residues (see Chapter 7), the use of residues for the production of building materials and from products sold to the general public (see Chapter 10).

Level 3: Dose criteria

Radiation protection means controlling relevant exposures and, where necessary, reducing them as far as reasonably practicable. To do this, exposures must be quantified as dose values and compared with standards.

It is well established that activities that result in low doses for which regulatory control is not necessary should be exempt from regulatory radiation protection. Overall, two approaches are used. The first concerns the dose received, and the second concerns the activity concentration of the material being handled or processed.

[4] In the US specific rules and limits are applied. (see Level 3)

Worldwide, there are different approaches to determining the exemption level. The IAEA recommends a dose value of 1 mSv per year [5], while some countries (Belgium, Italy) have set a threshold of 0.3 mSv per year. In practice, the exemption values for activity concentration serve as a more direct (and in many cases, simpler) method for determining exemption. This is because they can be verified directly by measurement. See Table 2-8 for values.

Dose limits are values that must not be exceeded during activities under a radiation protection regime. As with the exemption, the values implemented in national regulations differ. The values recommended in ICRP 103 are compiled in Table 2-9.

Between the exemption values and the dose limits is a wide range of optimization opportunities. The use of reference values or dose constraints as operational control values may support the process.

TABLE 2-8: EXEMPTION VALUES (EXAMPLES)

	U-238-series	Th-232-series	K-40
IAEA (and many national regulations)	1 Bq/g for each radionuclide	1 Bq/g for each radionuclide	10 Bq/g
Germany	0.2 Bq/g for each radionuclide	0.2 Bq/g for each radionuclide	0.2 Bq/g (added in consumer products)
Belgium	0.5 Bq/g	0.5 Bq/g	5 Bq/g
U.S.A.	U and Th mill tailings cleanup criteria is 5 pCi/g (0.185 Bq/g) > background. All others, case by case. ANSI guidance is 3 pCi/g (0,111 Bq/g) > background		

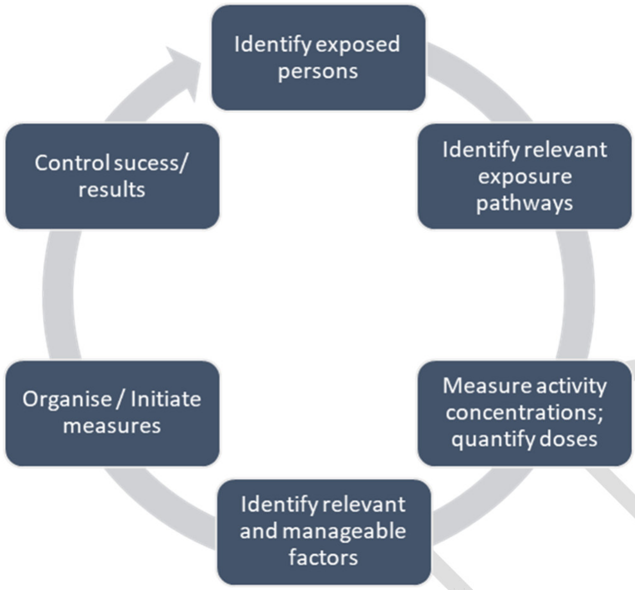
TABLE 2-9: RECOMMENDED DOSE LIMITS IN PLANNED EXPOSURE SITUATIONS. FROM ICRP 103

Type of limit	Occupational	Public	Comments
Effective dose in a year	20 mSv, maximum 50 mSv	1 mSv r	In the US, the limit for a fetus is 10% of the occupational (5x public) limit [24].
Effective dose in a 5-year period	100 mSv (20 mSv per year averaged)	(*)	(*) In special circumstances, a higher value in a single year can be allowed, provided that the average over 5 years does not exceed 1 mSv per year.
Annual equivalent dose in:			
Lens of the eye	150 mSv	15 mSv	
Skin	500 mSv	50 mSv	Averaged over 1 cm^2 area of skin, regardless of the area exposed.
Hands and feet	500 mSv	–	

Level 4: Practical application

This level brings together the theoretical system and aims to apply it in practice. It is the responsibility of practitioners to understand the framework and look to implement it as best as possible. While the ultimate responsibility for safety at a facility rests with the manager, the practitioner and manager work together to ensure a safe workplace and compliance with regulatory requirements. As a basis for their work, they must make accurate assessments and propose appropriate management decisions. How this can be done is the content of this handbook.

2.3.4 How to proceed in practice?



Radiation protection is a structured process that can be logically organized and managed. In Figure 2-9 the central elements are presented as a simple cyclic process. In the following sections, we describe some aspects of implementing the individual steps in this cycle in practice.

FIGURE 2-9: RADIATION PROTECTION PROCESS.

2.3.5 How to identify the persons?

To identify the exposed persons, the practitioner should have a good understanding of the operations and the activities that are being undertaken. This includes a working knowledge of the different work groups at the operation and their specific tasks. This will require the practitioner to get "into the field" and speak with a range of staff from managers through to the workers themselves. This way, the practitioner will have an understanding of which workers or work groups may be exposed and, therefore, require monitoring or controls.

In the occupational hygiene areas, "similar exposure groups" (commonly known as SEGs) are used to classify workers for the purposes of control and monitoring, and a similar method can be used for radiation protection. All workers in a group undertake similar roles (such as truck driving) and can be homogeneous.

Workers are typically adult individuals who share similar characteristics regarding the RP requirements. There is one exception: **women of reproductive age** may need special consideration.

Because industries involving NORM may emit liquid or gaseous discharges with radioactive contamination, we have to guarantee the protection of **members of the public**, too. To assess the exposure of these persons, they are represented by reference persons in **6 age groups.**

2.3.6 How are doses quantified?

What types of doses must we consider?

NORM exposure does not pose an "emergency situation" as described by ICRP since the concentrations and exposures do not present acute radiation hazards. Rather, the focus is on chronic or episodic exposure over time, and the **effective dose E** is the central measure of dose. It provides a standardized measure of impact that can take into account exposures from external and internal sources [25]. Its SI unit is **Sievert, Sv**.

> **Note:** Information on the use of different dose quantities in RP is contained in ICRP Publication 147: Use of Dose Quantities in Radiological Protection [25].

From a practical perspective, computer software, such as RESRAD and RESRAD-OFFSITE [26], is often used to calculate doses to various receptors. It is important that, as a practitioner, you do not use software systems blindly. You should be able to understand the inputs, the outputs, and the level of uncertainty. You should also be able to interpret the results obtained. The following items must be considered:

1. The effective dose a person receives accumulates over their whole lifetime. For practical purposes, the **annual effective dose** is commonly used as a reference. For individuals with high exposure, the lifetime dose may also be a relevant consideration.
2. The effective dose is the quantity in which dose limits, dose constraints, and reference levels are expressed.
3. The effective dose refers to the amount of radiation that an individual receives. This individual is referred to as a **model person** who is a summary of the behaviors of a (fictional or real) range of **individual persons** with the standardized properties of a **reference person** (see Table 2-10).
4. The effective dose cannot be measured and **must be estimated from measurable quantities.**
5. The effective dose due to internal exposure after inhalation or ingestion is a **committed effective dose** that includes (in the dose coefficients) the radiation effects of an incorporated radionuclide, depending on its biokinetic over a period of 50 years for adults, and to age 70 years for children (ICRP 103). For that reason, short-lived radionuclides have low dose coefficients and can be disregarded in most cases. This does not apply to radon, thoron, or their short-lived decay products.
6. When assessing low doses, it is important to know that the levels you are assessing are like natural background levels, and the radionuclides also occur naturally. So, make sure that you only consider the increment above the natural background when assessing operation-originated dose impacts.

TABLE 2-10: BOTH COMPONENTS OF A MODEL PERSON FOR DOSE ESTIMATION

Individual person	**Reference Person**
An idealized person whose case-specific behavior is the basis of dose estimations in a single case. The most relevant case-specific parameter is the exposure time. Other case-specific parameters may be: • reduction factors for shielding or • effects of personal protective equipment (PPE).	An idealized person for whom the organ or tissue equivalent doses are calculated by averaging the corresponding doses of the Reference Male and Reference Female. The properties of the Reference Person are independent of the single case. They are summarized in dose coefficients. The ICRP considers the Reference Persons • Worker and • 6 age groups for members of the public. The equivalent doses of the Reference Person are used for the calculation of the effective dose by multiplying these doses by the corresponding tissue weighting factors.

In practice, the effective dose of a person "p" can be determined as the sum of doses that are attributed to different **exposure pathways**:

$$\boldsymbol{E_p = E_{Ext,p} + E_{Inh,p} + E_{ing,p}}$$ EQU. 2-4

With

$E_{Ext,p}$ Dose of person p from external exposure,

$E_{Inh,p}$ Dose of person p from inhalation of radionuclides

$E_{ing,p}$ Dose of person p from ingestion of radionuclides

These three components of the effective dose can be calculated from measured quantities using the following approaches.

In the following, we consider the dose a person receives who works or is at a single site. If this person is exposed at multiple sites within a year, the doses received must be summed up.

External dose

The external dose can be measured as the **personal dose equivalent** $H_p(10)$ with a personal film badge dosimeter or TLD/OSLD dosimeter. Such dosimeters are prepared, distributed and evaluated by specialized companies or institutions, usually approved by authorities. They are standard for monitoring workplaces with roughly similar dose rates over time. If single events may occur that cause short-term doses close to the limit values, electronic personal dosimeters should be used. There are also tissue equivalent dose rate meters that read out in dose (usually plastic scintillators).

Note: / Practitioners' advice: Film dosimeters with a detection limit of 0.1 mSv cannot confirm that the annual dose remained below 1 mSv if they are changed monthly. To demonstrate compliance with the 1 mSv limit, longer wearing times of 2 or 3 months have been proven practicable.

OSL badges have a much lower detection limit and can meet the 1 mSv/y requirement. Gamma scintillometers should be cross-calibrated with a certified pressurized ion chamber (PIC), which is considered a secondary standard. This way, a site-specific curve can be developed.

For planning purposes or to estimate external doses at workplaces with large NORM amounts (e.g., tailing ponds, heaps, contaminated ground), measurements of the ambient dose rate (ADR) can be used. The ADR is the rate of the ambient dose equivalent H*(10).

The external effective dose can be calculated via:

$$\boldsymbol{E_{Ext,p} = f_{con} \cdot ADR_p \cdot t_{exp}} \qquad \text{EQU. 2-5}$$

With

f_{con} · Dose conversion coefficient, ambient dose equivalent H*(10) to effective dose E. The default value for workers or adults in a homogeneous radiation field is 0.7. For children or other radiation fields, other values have to be applied (see Appendix).

Note: for conservative estimations, f_{con} = 1 can be applied.

ADR_p (Representative) ambient dose rate at a site where the person p is during the exposure period. It is commonly measured in µSv/h or nSv/h at a height of one meter.

$t_{exp,p}$ Exposure period, i.e. the time the person p is (annually at the site with the ADR_p [h].

Note: In some countries, the excess external effective dose is calculated with the natural background subtracted.

Except for deep underground mines, the measured ambient dose rate includes a (small) contribution of cosmic radiation (about 0.04 µSv/h).

For the ambient dose rate of a homogeneous contaminated soil, UNSCEAR ([27] para 81) has published dose coefficients

$$\boldsymbol{ADR\left(\mu\frac{Sv}{h}\right) = 0.462 \cdot C_{U-238} + 0.604 \cdot C_{Th-232} + 0.0417 \cdot C_{K-40}} \qquad \text{EQU. 2-6}$$

C_{U-238} Activity concentration of the U-238-series in Bq/kg

C_{Th-232} Activity concentration of the U-238-series in Bq/g

C_{K-40} Activity concentration of K-40 in Bq/g

The dose coefficients in Equ. 2-6 are valid for decay series in a secular equilibrium. Dose coefficients for specific radionuclides and contaminated layers of different thickness published by the US EPA [28] are given in the Appendix.

Inhalation dose

Regarding the exposure by inhalation, two different types must be distinguished:

1. Inhalation of radon, in particular Rn-222, but in cases with natural thorium also Rn-220.
2. Inhalation of dust.

Inhalation of radon is described in Section 2.4.

The inhalation of dust results in the incorporation of long-lived NOR, which, depending on their biochemical properties, remain to a different degree over different times in the tissues of the human body. Because the decay of these radionuclides also makes doses when inhalation is terminated, the effective dose from inhalation is a committed dose. (See Section "What types of doses must we consider?")

A consequence of the concept of committed dose is that short-lived radionuclides have low inhalation dose coefficients.

The effective annual dose $E_{Inh,p}$ of person p from inhalation of dust is calculated as follows:

$$\boldsymbol{E_{Inh,p} = \dot{V} \cdot t_{Exp,p} \cdot f_R \cdot \sum_r g_{r,p*} \cdot C_{r,p}^{Air}} \qquad \text{EQU. 2-7}$$

Where

$\dot{V}$ Breathing rate [m^3 h^{-1}]; default value for workers 1.2 m^3/h. For members of the public, see Appendix.

$t_{exp,p}$ Exposure period [h (per year)], i.e., the time the person p is (annually) at the exposure site with the activity concentration C_r

f_R Reduction factor from air to inhalation due to personal protection measures.

$g_{r,p*}$ Inhalation dose coefficient for radionuclide r and reference person p* [Sv Bq^{-1}].

These dose coefficients depend on the particle size ("AMAD") and the chemical form in which the radionuclides occur. Data and additional explanations are given in the Appendix.

$C_{r,p}^{Air}$ Activity concentration of the particle-bound radionuclide r in air [Bq m^{-3}] at the exposure site of person p.

Frequently, the activity concentration in air is not measured, or measurements identify only a single typical radionuclide. Possibilities to proceed if the activity concentration was not measured are described below (see Equ. 2-8). How to proceed if only some radionuclides have been measured is described in Chapter 5.

Because short-lived radionuclides do not or only to a negligible degree contribute to the committed dose (see above), the following long-lived radionuclides need to be considered for the calculation of the inhalation dose in general:

- U-238 series: U-238, U-234, Th-230, Ra-226, Pb-210, Po-210,
- Th-232 series: Th-232, Ra-228, Th-228.

In exceptional cases, Pa-231, Ac-227 from the U-235 series can contribute to the dose, too.

Dose coefficients for these radionuclides are given in the Appendix. Because of their high dose coefficients (see Figure 2-10) thorium isotopes (including Th-230) need particularly careful consideration.

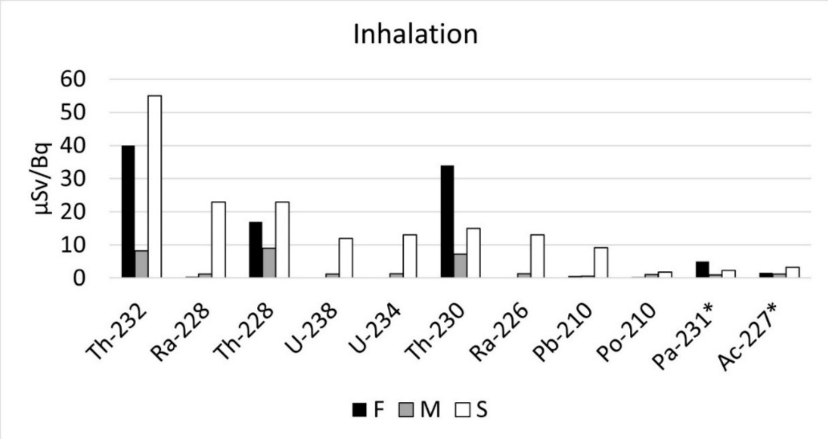


FIGURE 2-10: INHALATION DOSE COEFFICIENTS FOR WORKERS FOR LONG-LIVED DECAY-SERIES RADIONUCLIDES (ICRP 137 [29]). F, M, S ARE DIFFERENT ABSORPTION TYPES. VALUES FOR PA-231 AND AC-227 ARE MARKED WITH * BECAUSE THEY ARE REDUCED BY A FACTOR OF 20 TO CONSIDER THE ACTIVITY CONCENTRATION RATIO U-235/U-238 OF ABOUT 0.05.

Notes / Practical advice:

1. It is not necessary to apply the highest values for the different absorption classes. Because the chemical forms in which the radionuclides exist in NORM are roughly known, the values marked in the Appendix should be preferred.
2. Background inhalation doses have to be calculated for the same time $t_{exp,p}$, the model person is exposed.
3. Background concentrations in air are compiled in Table 2-11 and Table 2-13.
4. Background concentrations of Pb-210 and Po-210 in the air result from the decay of Rn-222. They are significantly higher than the values calculated from soil activity concentrations. Reference values are given in Table 2-13.

   Note:

   Pb-210 concentrations in air are generally reflective of the land-sea distribution with lower values in coastal areas due to the low radon exhalation of the sea [30].

   With a typical PM10 dust concentration in clean air regions of humic and densely vegetated areas in Europe of 20 -40 µg/m³ (2E-8 kg/m³) [31], the activity concentration of Pb-210 of 300 - 500 µBq/m³ results in an activity concentration in dust particles of 8 – 25 Bq/g! Consequently, environmental dust collected in air filters can exceed the exemption values!

In the absence of a site-specific value, the activity concentration in air may be estimated based on the level of activity concentration of NORM, using a reference value of airborne particle concentration:

$$C_r^{Air} = C_r^{NORM} \cdot f_d \cdot C_{dust}^{Air} \cdot CF \qquad \text{EQU. 2-8}$$

Where:

C_r^{NORM} Activity concentration of radionuclide r in the soil (Bq/kg)

C_{dust}^{Air} · Dust concentration in the air (kg/m³)

f_d Dilution factor (-)

CF Concentration factor that describes the ratio of activity concentrations in the inhalable fraction (particle diameter smaller than 0.02 mm) to the activity concentration in the total soil (measured as the fraction with particle diameter < 2 mm).

Dust concentrations are highly variable in time and particle size distribution. The value used for calculating the inhalation dose should ideally represent the average concentration of the inhalable fraction during the exposure period. In many cases, determining this average dust concentration is challenging. As a substitute, typical values for working procedures taken from the literature are compiled in Table 2-11.

Since airborne dust at an exposure site can originate from various sources, IAEA SRS 44 also accounts for dilution factors f_d ranging from 1 (undiluted) to 0.1. For residents living in the vicinity of a landfill or other facility, a dilution factor 0.1 is applied [35]. A dilution factor can also be applied for persons living in a house if dust concentrations outside the house have been modeled or otherwise estimated.

TABLE 2-11: DUST CONCENTRATION VALUES

	Concentration	**Reference**
Workplaces, realistic scenario	0.5 mg/m³	IAEA SRS 44 [35]
Workplaces, low probability	1 mg/m³	
Outside facilities, realistic assumption	0.1 mg/m³	
Outside facilities, low probability	0.5 mg/m³	
Dust concentration with processing procedures	2 mg/m³	EC RP 122-II [32]
Dust concentration without processing procedures	1 mg/m³ - Ash, sand 0.5 mg/m³ - Rock, Slag	
Stockpiles (normal)	1 mg/m³	EC RP 95 [33]
Stockpiles (unlikely)	5 mg/m³	
Fume	1 mg/m³	
Soil, mining residues	0.5 mg/m³	Germany [34]
Background	0.05 mg/m³	

Because the activity distribution over particle sizes may show higher activity concentrations in fine particles, activity concentration factors are applied. Values of CF mentioned in the literature are given in Table 2-12.

TABLE 2-12: ACTIVITY CONCENTRATION FACTORS CF FOR THE INHALABLE FRACTION OF DUST

Dust source	**CF**		**Reference**
Materials other than those from smelting processes	4		IAEA [35]
Soil, mining residues	4	fraction < 0.02 mm	Germany [34]
Material of the type “rock/earth” or “ash”	2		RP 122 Part II [32]
Other types of material	1		

TABLE 2-13: ***VALUES OF NATURAL BACKGROUND ACTIVITY CONCENTRATION C FOR A PARTICLE-BOUND RADIONUCLIDE r***

Radionuclide r	UNSCEAR [3]	Germany [34]
	µBq/m³	µBq/m³
U-238; U-234	1	10
Th-230	0.5	10
Ra-226	1	10
Pb-210	500	310
Po-210	50	40
Th-232	0.5	8
Ra-228	1	8
Th-228	1	8
U-235	0.05	0.5
Pa-231	--	0.5
Ac-227	--	0.5

Note: / Practitioners' advice

Some workplace situations require the use of respiratory protection. The reason is frequently not the radioactivity, but the adverse properties of dust due to its chemical or physical properties.

To assess the effects of respirators on the inhalation dose, the dust protection factor f_R according to Equ. 2-7 can be applied. Some factors for typical respirators are given in Table 2-14.

TABLE 2-14: ***DUST PROTECTION FACTORS OF RESPIRATORS***

Mask type	f_R	Comment
FFP-1 Half mask	0.22 – 0.25	Penetration according to European Standard EN 149:2009-8. Leakage under practical conditions is considered.
FFP-2 Half mask	0.08 – 0.11	
FFP-3 Half mask	0.02 – 0.05	
Half-face paper masks	0.5	Practitioners approach India
fitted half-face masks	0.1	
airstreams or air supplied	0.02	
Half-face	0.1	Other practitioners' approaches
Full-face	0.02	
Fresh airline	0.001	
self-breathing apparatus back-pack	(1 – 5)E-4	

Note: Respirators reduce the concentration of inhaled dust but also shift particle sizes to lower diameters because coarser particles are more retained in the mask than smaller particles.

When applying a factor f_R, the following should be considered:

- The retention of the mask tissues is very high (99+ %). However, masks that don't cover the entire face (unlike those rubber face pieces) have a leak rate. The dust reduction factors of the European norm EN 149:2009-08 and practitioners' approaches from India consider this.

- Unless strictly supervised, workers tend to remove their protective equipment or wear it in not properly. Therefore, in the first round of dose calculation, no reduction factor should be applied ($f_R = 1$).
- If the calculations are used for authorized radiation control, standardized values should be approved by national regulatory authorities

Ingestion dose of workers

People will not intentionally ingest radionuclides; however, poor housekeeping and hygiene standards may result in ingestion (for example, if workers are dirty when eating lunch). If workers ingest NORM particles during their work, this type of incorporation is referred to as ingestion. In typical work situations, ingestion results in significantly lower doses than inhalation.

Note that it is more likely that members of the public may receive doses from the consumption of locally produced food affected by discharges from the processing of NORM. Such cases are not considered in this handbook. If needed, the following guidelines can be used:

- RESRAD (USA). Available at https://resrad.evs.anl.gov/
- Calculation Guideline Mining (Germany) [34]. PDF booklet with formulas and data. Dose coefficients are from ICRP 65.

Analog to inhalation, the ingestion results in the incorporation of long-lived NOR, and the effective dose from ingestion is a committed dose to which short-lived radionuclides contribute only to a minor degree.

The effective annual dose $E_{Ing,p}$ of person p from ingestion of NORM-particles is calculated as follows:

$$\boldsymbol{E_{Ing,p} = \dot{m}_p \cdot t_{Exp,p} \cdot CR \cdot \sum_r g_{ing,r,p*} \cdot C_{r,p}} \qquad \text{EQU. 2-9}$$

Where

$\dot{m}_p$ Ingestion rate of person p. Exemplary values for normal assumptions are 1.25 mg/h (stockpiles) and 5 mg/h (scales and residues) given in [36] or 6 mg/h [34].

$t_{exp,p}$ Exposure period [h (per year)], i.e., the time the person p is (annually) at the exposure site with the activity concentration C_r

CR Concentration factor from NORM to ingested particles. Default value is 2 [34], [35].

$g_{r,p*}$ Ingestion dose coefficient for radionuclide r and reference person p* [Sv Bq^{-1}].

The dose coefficients for workers given in ICRP 137 [37] are valid for all chemical forms, except for uranium. Data and additional explanations are given in the Appendix.

$C_{r,p}$ Activity concentration of radionuclide r in NORM [Bq g^{-1}] at the working place of person p.

Dose coefficients for the long-lived radionuclides shown in Figure 2-11demonstrate that, unlike inhalation, radium isotopes and Pb-210, Po-210 have the highest dose coefficients.

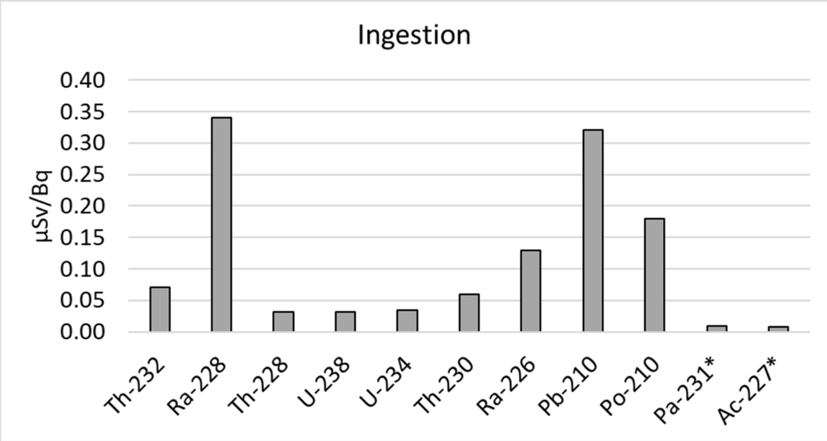


FIGURE 2-11: INGESTION DOSE COEFFICIENTS FOR WORKERS FOR LONG-LIVED DECAY-SERIES RADIONUCLIDES (ICRP 137 [29]). VALUES FOR PA-231 AND AC-227 ARE MARKED WITH * BECAUSE THEY ARE REDUCED BY A FACTOR OF 20 TO CONSIDER THE ACTIVITY CONCENTRATION RATIO U-235/U-238 OF ABOUT 0.05.

2.3.7 How to identify manageable factors for RP in industries involving NORM?

Most planned uses of radiation involve discrete sources with man-made radionuclides specifically designed for such use. Therefore, radiation protection is typically based on handling geometrically small radiation sources. For this type of source, the Inverse Square Law holds. This law describes the rate at which gamma radiation intensity decreases from a source. If the radiation is caused by a very small source, the inverse square law holds:

$$\frac{I_2}{I_1} = \frac{d_1^2}{d_2^2} \qquad \text{EQU. 2-10}$$

and states the intensity of the radiation I (measured as H*(10) or ADR) goes down by the square of the distance d from the source (Figure 2-12). For instance, if you move twice as far from the source, the intensity of the radiation will decrease by a factor of 4. As the distance doubles, the area quadruples and thus, the initial radiation amount is spread over that entire area and is therefore reduced proportionately. The underlying cause for this is geometric dilution corresponding to point-source radiation into three-dimensional space.

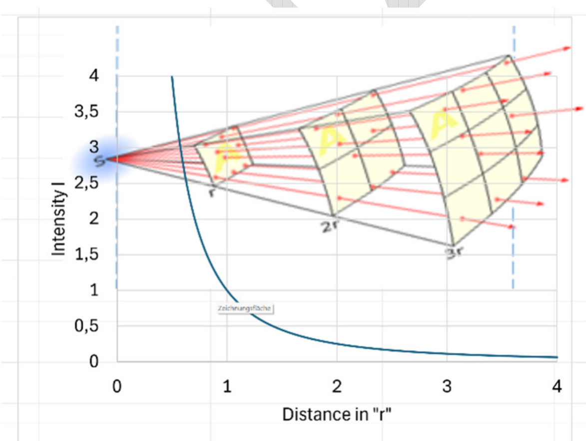


FIGURE 2-12: DOSE RATE REDUCTION ACCORDING TO THE INVERSE SQUARE.

Diagram made by authors. Included figure from Wikipedia (CC-License)

This inverse square law is at the heart of the three basic rules of traditional radiation safety: time, distance and shielding. However, as also stated in Figure 2-12, NORM in industry exists frequently in bulk amounts, as large stockpiles or even radioactively contaminated ground. For larger area sources:

1. The dose rate reduces as the inverse of the distance (not the square of the distance).
2. The inverse square law then applies when the area source is approximated as a "point source" which (by rule of thumb) is approximately ten times the facing length.
3. Large stockpiles may have skyshine[5] that interferes with ground surveys near large sources. Collimated detectors are recommended in those areas.

Because the technical processes of a plant or facility are usually fixed and unchangeable, the factors for managing RP are:

- Good design: work areas should be (if possible) away from the most relevant exposure sources.
- Exposure time: At sites with high dose rate, the workers should be stay only as long as required.
- Shielding: Sources should be shielded with appropriate walls (lead shielding is rarely necessary).
- Distance: workers should leave areas with high dose rates during breaks.
- Dust: Avoiding or at least reducing dust generation e.g. by moistening.
- Use of personal protective equipment (including respiratory protection)
- Personal hygiene (washing hands), donning and doffing of PPE.
- Ongoing "housekeeping" – small spills cleaned up quickly, debris removed quickly.
- Communication on radioactivity: information, work instructions, job safety analyses, marking of areas with significantly enhanced potential exposures (high dose rates, high dust concentrations). See Chapter 9.

How to do this in practice is described in Chapter 6.

2.3.8 What indices are helpful – and what are not?

In the international literature, various indices are frequently used to characterize NORM. In this section, the most common of these indices are shown and briefly discussed regarding their applicability for NORM and radiation protection purposes.

Most of these indices, except the Excess Lifetime Risk, were introduced to characterize the radioactivity of building materials. The indices make some assumptions about the radionuclides' equilibrium status because building materials are usually derived from minerals rather than processed materials. Radioactive equilibrium can be assumed in the U-238 and the Th-232 series, and therefore, the reference to Ra-226 to represent the U-238 series is correct. Despite being a long-time-established convention, the reference to Th-232 is not accurate because it refers to Ra-228 and its daughter Ac-228 as the gamma emitter in the Th-232 decay series.

[5] Skyshine is when gamma from the source can reflect from clouds or other atmospheric conditions.

In the following equations, C_{Ra-226}, C_{Th-232}, and C_{K40} are the activity concentrations of Ra-226, Th-232 (Ra-228), and K-40 in Bq/kg.

The external hazard index (H_{ex})

This index was introduced by Beretka and Mathew [38] and is calculated as follows:

$$H_{ex} = \frac{C_{Ra-226}}{370} + \frac{C_{Th-232}}{259} + \frac{C_{K-40}}{4810} \qquad \text{EQU. 2-11}$$

The index evaluates the indoor exposure to gamma radiation from the natural radionuclides in building materials of dwellings. If the index value is less than unity, the radiation hazard is classified as insignificant.

Gamma Index (I_γ)

In 1999 the European Commission published a guidance [39] on principles concerning the natural radioactivity of building materials. In this guidance, the following gamma-Index Iγ was introduced

$$I_\gamma = \frac{C_{Ra-226}}{300} + \frac{C_{Th-232}}{200} + \frac{C_{K-40}}{3000} \qquad \text{EQU. 2-12}$$

This index became a legally binding provision when it was included in Annex VIII of Directive 2013/59/Euratom. If the index is applied to materials used in bulk amounts, e.g., concrete, values, $I_\gamma \leq 0.5$ represents a dose of less than 0.3 mSv per year, and $I_\gamma \leq 1$ a dose of less than 1 mSv per year.

For superficial and other materials with restricted use: tiles, boards, etc., the value of $I_\gamma \leq 2$ corresponds to a dose rate value of 0.3 mSv, whereas $I_\gamma \leq 6$ corresponds to a value of 1 mSv per year. It is explicitly stated in [39] that the "*index should be used only as a screening tool for identifying materials which might be of concern. Any actual decision on restricting the use of a material should be based on a separate dose assessment.*"

Alpha index (I_α)

In some publications (e.g. [38]), an alpha index (I_α) is applied, which is calculated as follows,

$$I_\alpha = \frac{C_{Ra-226}}{200} \qquad \text{EQU. 2-13}$$

For a value of $I_\alpha = 1$, this index is equivalent to a Ra-226 concentration of 200 Bq·kg^{-1} and is primarily used as an indicator for radon exhalation from such material, which could cause the indoor radon concentration to exceed 200 Bq·m^{-1}, which is considered to be hazardous.

Radium equivalent $C_{Ra-equiv}$

The radium equivalent index is a fictitious radium concentration that gives the same gamma dose rate as the mixture of NOR in a specific material. It is calculated according to

$$C_{Ra-equiv} = C_{Ra-226} + 1.43 \cdot C_{Th-232} + 0.077 \cdot C_{K-40} \qquad \text{EQU. 2-14}$$

or, using the "External hazard index" (see equation 2-9):

$$C_{Ra-equiv} = 370 \cdot H_{ex} \qquad \text{EQU. 2-15}$$

The constants in Equ. 2-13 represent the ratios of the dose rate coefficients Th-232sec/Ra-226+ and K-40/Ra-226+. The values may differ depending on the applied coefficients.

In summary, it is important to note that the indices summarized above were developed as screening tools for building materials. They are not generally helpful for characterizing NORM at workplaces in mining or industry. However, they may be useful when residues are used as additives to building materials.

The radium equivalent can be helpful in comparing NORM of different compositions.

The **excess lifetime cancer risk (ELCR)** is defined as

$$\boldsymbol{ELCR = E_{ex} \times T \times R} \qquad \text{EQU. 2-16}$$

where E_{ex} is the annual effective dose rate **excess** (mSv), T is the average lifetime (70 years), and R is the risk due to stochastic effect with a value of 0.05 Sv^{-1} according to ICRP Publication 103 [20]. ELCR is frequently misused, and caution in its use should be exercised. As noted earlier in this handbook, the basis of radiation protection is the LNT, despite there being no evidence of effects at doses typically found in the NORM area. The exception to this is exposure to radon.

The ELCR is a useful indicator in optimization assessments and also in cases where workers have been exposed at levels near to or exceeding the dose limit (20 mSv per year; 100 mSv in 5 years). The calculation of excess risks from natural radiation without any anthropogenic excess contamination is unscientific (cf. [40]).

2.3.9 Case Study on Exclusion and Exposure

Exclusion and exemption are fundamental concepts in RP. They are briefly described in Section 2.3.1. Their application to NORM can be complex because the distinction between background and operational impact can be difficult in certain cases.

Introduction remark: The following description is generalized from a real case. The exposure data are for illustration only. The aim of this case study is for the reader to consider the different ways that the concepts of "background radiation", NORM, and existing exposure situations are applied in real-world cases. This case study shows that the way you "think about" radiation exposure defines the radiation exposure.

A modern open-cast mine for niobium-tantalum ores is located in an isolated region far away from larger settlements. The region is sparsely populated, but several hundred local people live in a village on the edge of the mining area. The climate is tropical, and the vegetation outside the devastated mining areas is dense. Unless it rains, the soil can become dry.

The mining region is part of a "high-background area" with common ambient dose rates (ADR) ranging from 0.5 to 1 µSv/h. The workers live in lightweight houses in a camp in this area. They spend about 8 months of the year in the camp, working 48 hours a week during this time. They also spend their free time in the camp. An ADR of 0.8 µSv/h was measured in a dormitory in the camp. Approximately four months of the year, the workers live with their families in other parts of the country.

Besides the direct mechanical extraction of the ores, the operation is combined with ore beneficiation involving crushing, grinding, and classification to produce concentrates.

The workers are well-equipped. The company provides them with work clothes and personal protective equipment.

At individual workstations where concentrate residues have accumulated, dose rates of up to 20 µSv/h were measured. The dose received by workers at workplaces with particularly high exposure levels is monitored using personal dosimeters. The dosimeters show an average of 0.7 mSv per month.

Measurement of gamma radiation levels on the boundary of the project area (where Indigenous people may be present) is about 0.8 µSv/h.

The average effective annual dose in the country is published to be 2.2 mSv.

Results of dose considerations for workers and local residents are compiled in Table 2-15.

TABLE 2-15: ANNUAL EFFECTIVE DOSE VALUES OF A HIGHLY EXPOSED WORKER AND A LOCAL RESIDENT IN THE MINING REGION

	Unit	**Worker**			**Local resident**
		Work	Spare time	Home	Adult
Site characteristics					
U-238sec	Bq/g	1.2	0.16	0.03	0.16
Th-232sec	Bq/g	7.2	0.96	0.03	0.96
Ambient dose rate (site)	µGy/h	5.0	0.75	0.13	0.75
Exposure					
Exposure time	H	1600	4250	2910	8760
$E_{external}$	mSv	5.56	2.23	0.27	4.59
$E_{inhalation}$	mSv	0.94	0.03	0.00	0.05
$\mathbf{E_{Total}}$	**mSv**	**6.49**	**2.25**	**0.27**	**4.64**
	µSv/h	**4.06**	**0.53**	**0.09**	**0.53**

The radiation protection officer must decide on the operational dose the worker receives. He/she gets the following proposals (A to F), along with a brief explanation.

A	1.85 mSv (=6.49 – 4.64)	This is the incremental increase in the natural background radiation in the mining region to which the local people are exposed.
B	5.63 mSv (=6.49 – 0.86)	Similar to before, but the background radiation referred to the working time (1600 h x)
C	6.49 mSv	Because this dose is obtained during work.
D	6.49 mSv	Because the activity concentration of the soil is below the exemption value of 1 Bq/g, and consequently, exposure during spare time must not be considered.
E	8.74 mSv (=6.49 + 2.25)	Because this is the dose a worker receives due to his/her professional activities in general
F	9.01 mSv (=6.49+2.25+0.27)	Because this is the total dose the worker is exposed to in a year

The same holds for the question of whether local inhabitants need to be protected against radiation. The following options (G – J) are available:

G	0 mSv	Because the natural background is excluded from RP
H	0 mSv	Because the activity concentration of the soil is below the exemption value of 1 Bq/g, consequently, exposure must not be considered.
I	4.64 mSv	Because this is the total dose the public is exposed in a year
J	2.44 mSv (4.64-2.20)	Because this is the excess to the average dose for adults in the country

The Task Group members have discussed the options and voted for workers for **C – D – E** and for residents for **G - H.** The different answers demonstrate that basic parts of the RP system, such as the background, are not very clear in individual cases. However, the Task Group members agreed that calculating an ELCR for the local highly exposed population is neither correct, as no "excess" occurs, nor useful for RP purposes.

2.3.10 How to get further information?

There are many textbooks available on radiation protection. However, most of them are focused on radiation protection in planned exposure situations where radionuclides are utilized for their radioactive properties. These textbooks may help to get more detailed information about dose concepts.

J. E. Turner: The Physics of Radiation and Radioactivity [41]

Level: Upper Undergraduate / Graduate. **Focus:** Radiation interactions, dosimetry, and biological effects. **Great for:** Health physics, radiation protection, and environmental applications.

For advanced readers, the ICRP Publication 103 [20] can be recommended as a sound basis for clarification of the basic terms and concepts in radiation protection.

The IAEA also produces many practical guidance documents.

2.4 Radon and NORM

2.4.1 Introduction

In this section, we look at radon in industries involving NORM. There have been many books, publications, and papers written on radon (see Section 2.4.9), and the objective is to provide a practical perspective on radon and provide some guidance and assistance on its management in workplaces.

In this section, we use the term "radon" as the isotope Rn-222 from the U-238 decay chain. We use the term "thoron" as the isotope Rn-220 from the Th-232 decay chain.

2.4.2 What basics are needed when dealing with radon? Background

Radon is a naturally occurring, inert radioactive gas found everywhere in the atmosphere. It is a decay product of Ra-226 in the U-238-series (Rn-222) and Ra-224 in the Th-232 series (Rn-220) that occur in soils, rocks, and water. When radon is produced by radioactive decay, it can diffuse into the atmosphere.

Rn-222 is known to be the leading cause of naturally occurring lung cancer and the second cause of lung cancer after smoking. Therefore, protection against radon is an essential task in RP. However, radon itself is not particularly hazardous. It is an inert gas and can be breathed in and out of the human lungs. Due to its 3.8 days half-life the probability of any single radon atom decaying in the human lungs is very low. Only at very high concentrations can Rn-222 represent a hazard.

The primary hazard from radon is from its short-lived decay products. Radon has four short-lived decay products: Po-218, Pb-214, Bi-214 and Po-214 (see Figure 2-13). These decay products emit two alpha particles and two beta particles in a short time (decay parameters see Table 2-16). Due to the alpha-recoil at decay, the decay products are charged particles of metallic chemical elements that can attach to fine aerosols in the air.

The activity concentration of the decay products depends upon their own half-lives, which are less than 30 minutes in the case of Rn-222. This means that the activity concentration of the decay products can quickly come into equilibrium with the radon concentration (Figure 2-14).

In contrast, the half-life of the decay products of Rn-220 is significantly longer than that of Rn-220 itself (Table 2-17). Therefore, the concentration and distribution of the decay products of Rn-220 are much more decoupled from Rn-220 than is the case with Rn-222.

In a practical sense, both radon isotopes, Rn-222 and Rn-220 can be considered to be the "transport mechanism" for the more hazardous decay products.

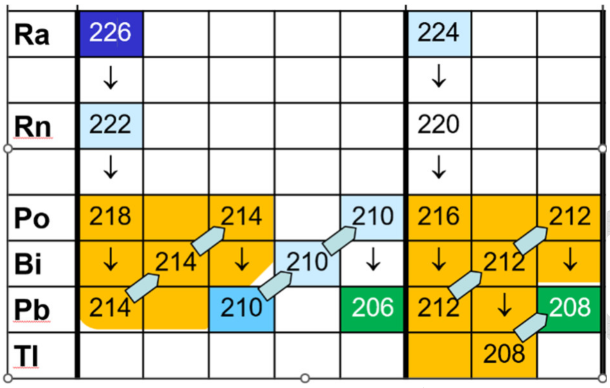


FIGURE 2-13: RADON ISOTOPES RN-222 AND RN-220 WITH ITS PRECURSORS AND DECAY PRODUCTS.

TABLE 2-16: DECAY PARAMETER OF RN-222 AND ITS SHORT-LIVED DECAY PRODUCTS.

Note: Energy of Beta rays is Mean Energy; P – emission probability of the decay mode (data from [42])

Nuclide	Mode	Half-life	Energy	P	Energy	P
Rn-222	α	3.82 d	5486 keV	99.9%	4987 keV	0.8%
Po-218	α	3.05 min	6110 keV	100%		
Pb-214	β	26.8 min	207 keV	48.9%	227	42.2%
Bi-214	β	19.7 min	1270 keV*	18.2%	540 keV*	17.8%
Po-214	α	1.60E-04 s	7830 keV	100%		

* There are many more beta emissions with a lower probability

TABLE 2-17: DECAY PARAMETER OF RN-220 AND ITS DECAY PRODUCTS.

Note: Energy of Beta rays is Mean Energy; P – emission probability of the decay mode (data from [42])

Nuclide	Mode	Half-life	Energy	P	Energy	P
Rn-220	α	55.6 s	6288 keV	100%		
Po-216	α	0.146 s	6777 keV	100%		
Pb-212	β	10.6 h	331 keV	83%	569 keV	12%
Bi-212	α (36%)	60.5 min	6090 keV	9.75%	6050 keV	25%
Bi-212	β (64%)		832 keV	55.5%	532 keV	4.4%
Po-212	α	3.00E-07 s	8780 keV	100%		
Tl-208	β	3.05 min	647 keV	48.7%	533 keV	21.8%

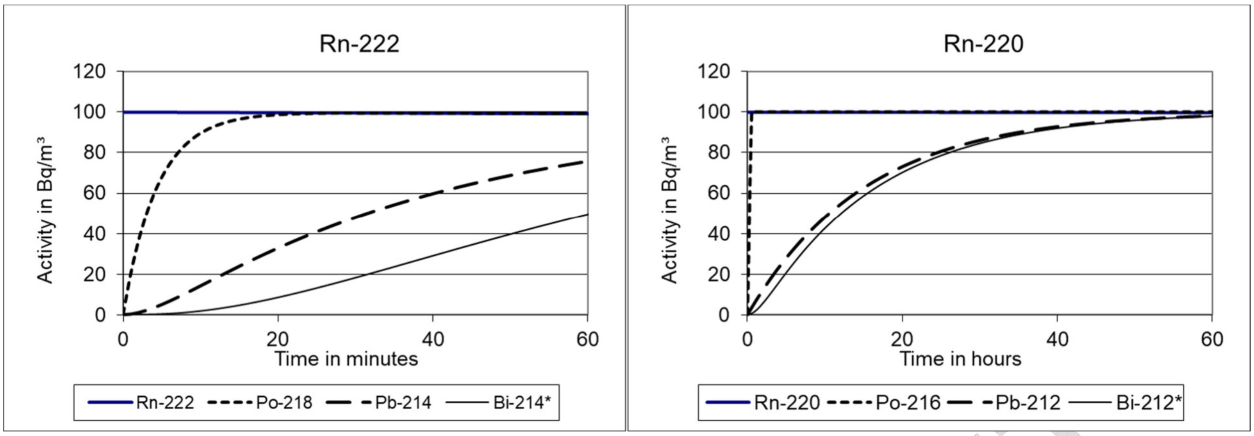


FIGURE 2-14: INGROWTH OF RADON DECAY PRODUCTS AT CONSTANT RADON OR THORON CONCENTRATIONS.

Note: Bi-214* means Bi-214 and Po-214 in activity equilibrium; Bi-212* means Bi-212 with Po-212 and Tl-208 in activity equilibrium. Note the different units of the X-axis!

When measuring radon in air, the units are activity concentrations (Bq/m^3) of radon. When measuring the decay product concentrations, the convention is to measure the energy of the alpha radiation from the decay products, expressed in µJ/m^3. This is important because **radon concentration is measured as an "activity concentration"**, while a **radon decay product concentration is measured as an "energy concentration"**.

The historically established unit level (WL) or working level month (WLM) is still used in some countries. The relations between WL/WLM and the SI-units are given in the Appendix.

The relationship between radon concentrations and the radon decay product concentrations depends upon the equilibrium factor (F). There can be quite large variations in equilibrium factors; however, long-term averages of equilibrium factors can be used to estimate doses from long-term averages of radon concentrations. For example, dose can be calculated from radon measurements and the reference value(s) for F.

There have been many studies on equilibrium factors, e.g. [43]. In general, the reported equilibrium factors are as follows:

- 0.6 for radon outdoors (Rn-222)
- 0.4 for radon indoors (Rn-222)
- Between 0.002 and 0.02 for Rn-220 (and noted to be highly variable).

In the case of Rn220, it is vital to note that its decay product has a much longer half-life than that of radon. The half-life of Pb-212 is nearly 11 hours, and this means this radionuclide stays long enough in the environment to react and distribute in the air according to its own rules. Therefore, nearly all studies indicate that it is better to measure thoron decay product concentrations rather than thoron concentrations.

When measuring Rn-220, the detectors must be very close to the surface due to the very short half-life. For Rn-220 decay products, samples should be collected in workplaces where exposure is occurring.

The RnDP concentration can then be the basis for a dose estimate. The general equation is as follows [44]:

- RnDP Conc. (µJ/m^3) = Radon concentration (Bq/m^3) x equilibrium factor (F) x recognised constant (K)
  - K_{Rn222} - 5.56 x 10^{-3} (µJ/m^3)/(Bq/m^3)
  - K_{Rn220} - 7.56 x 10^{-2} (µJ/m^3)/(Bq/m^3)

Radon can be built in enclosed spaces where there is a source of material with elevated concentrations of uranium or thorium.

A very helpful calculator can be found at: https://www.wise-uranium.org/rdcrn.html

2.4.3 Which quantities describe radon emissions?

The concentrations of radium - Ra-226 and/or Ra-224 - can be used to determine the material's potential as a radon source. However, the radon/thoron emanation can be affected by many factors, including the material's characteristics such as porosity and permeability, as well as environmental characteristics such as ventilation and pressure. Measuring radon is the best approach.

When describing the release of radon to the atmosphere, several terms are used, sometimes incorrectly and interchangeably. It is important to note that the terms are quite different.

- ***Emanation*** is a measure of the fraction of radon atoms, formed from the decay of radium, that escape from the material's grains [6] into the interstitial space between the material's grains. Emanation is quantified as a factor ranging from 0 to 1. Typically, for rocks, the factor is 0.2 (20%). Some values of the emanation factor of building materials and some NORM (slag, fly ash) are given in Table 2-18.
- ***Exhalation*** describes the measure of the bulk release of radon from a material. For comparison, the specific exhalation rate per unit surface area is useful.
- **Emission** is the total exhalation of a specific amount of material. For example, "this stockpile of rocks has an exhalation rate of X Bq/s". Such an emission rate can serve as a source term for atmospheric transport modeling.

TABLE 2-18: EMANATION FACTORS OF BUILDING MATERIALS AND NORM [45]

	Range in %	Mean in %
Bricks	0.01 – 14.5	1.3
Concrete (general)	4.0 – 40.6	13.6
Sand, gravel	6.9 – 40.9	12.7
Slag	0.28 – 0.42	0.36
Fly ash	0.06 – 10.7	1.7

The Rn-222 exhalation rate is a very complex quantity. Its value depends not only on the uranium (Ra-226) concentration in the material, but also on the emanation coefficient of the grains or rocks and the soil's gas permeability which among others depends on the soil moisture.

Based on the formulas given in the German Calculation Guide [34], the Rn-222 exhalation rate can be estimated with

$$J_{Rn-222} = \varepsilon \cdot EF \cdot \rho \cdot C_{Ra-226} \cdot \tanh\left(\frac{H}{H_{Ref}}\right) \qquad \text{Equ. 2-17}$$

Here J_{Rn-222} is the Rn-222 exhalation rate (Bq m^{-2} s^{-1}; ε is the exhalation coefficient (m s^{-1}); EF is the emanation factor (--); ρ is the soil density (g m^{-3}), C_{Ra-226} is the Ra-226 activity concentration (Bq/g), H is the thickness of a Ra-226 contaminated ground, and H_{Ref} is 2 m.

In [34], a conversion factor to estimate the Rn-222 exhalation rate from the Ra-226 activity concentration of the material of mine dump is given as 1 Bq m^{-2} s^{-1} at 1 Bq/g. In this Calculation Guide, a density of 2 Mg/m³ and an emanation factor of 0.2 are mentioned. Using these figures, the exhalation coefficient is calculated in Table 2-19. Similar values are obtained from other published data.

UNSCEAR [46] gives the global average radon-222 exhalation rate from soil, referring to an older paper [47] with 16 mBq m^{-2} s^{-1}.

The mean Rn-222 exhalation rate (flux) from soils in Europe is estimated to be 10 mBq m^{-2} s^{-1} or 15 mBq m^{-2} s^{-1} for the period 2006–2010 [48]. The corresponding seasonal variations with low fluxes in winter and high fluxes in summer range from ca. 7 to ca. 14 mBq m^{-2} s^{-1} and from ca. 11 to ca. 20 mBq m^{-2} s^{-1}, respectively.

Gold mining tailings in the Gauteng province, South Africa, were studied in [49] for the radon releases. The weighted average activity concentrations in the soil samples were 308 ± 7 Bq kg^{-1} for U-238. The average radon flux was found to be 120 ± 20 mBq m^{-2} s^{-1} for the mine dump.

From all these data, exhalation coefficients in the range of (1 – 3)E-06 m s^{-1} are estimated in Table 2-19. For a rough estimation of a background exhalation rate from an infinitely thick layer with a Ra-226 activity concentration C_{Ra-226}, an exhalation coefficient of **2E-06 m/s** can be applied. For specific areas like mine dumps or for specific climate conditions, adopted density values and emanation factors should be applied. If the contaminated horizon is less than 2 m thick the exhalation must be reduced according to Equ. 2-16.

TABLE 2-19: RN-222 EXHALATION PARAMETERS FOR INFINITE THICK SOIL LAYERS

	J_{Rn-222} In mBq m^{-2} s^{-1}	Density In g m^{-3}	Emanation factor	C_{Ra-226} In Bq/g	ε in m s^{-1}
Calculation value [34]	1000	2E+06	0.2	1	2.5E-6
World [46] [47]	16	1.5E+6	0.1 -0.2	0.04	(1.3 – 2.7)E-06
Europe [48]	10 – 15	1.5	0.1 – 0.2	(no data)	(0.8 – 2.5)E-06
Gold Mine tailings [49]	120	1.5	0.1 – 0.2	0.308	(1.3 – 2.6)E-06

2.4.4 Which sources contribute to radon at workplaces?

The primary source of radon in the outdoor and indoor environment is the Rn-222 produced by the decay of radium (Ra-226). While indoor radon comes mainly from the soil or the geological foundations of a site, the outdoor radon concentrations result from the atmospheric mixture of radon released from large areas. Building materials may contribute to indoor radon concentrations, but this contribution is usually less significant than the release from underground sources.

In industries involving NORM, the handling, processing or storage of bulk amounts of materials with significant activity concentrations of uranium or thorium series radionuclides can result in elevated emissions of radon or thoron, leading to exposures.

Examples include:

- Processing of ores or raw materials from areas with naturally high uranium or thorium
- Mineral sands and rare earth mining and processing
- Workplaces in areas with geology that has naturally higher levels of granite (which contains elevated uranium concentrations)

Therefore, radon activity concentrations at workplaces may come from two sources: the geogenic foundation (including building materials) and the radon released from NORM. Although exposure is independent of the origin, a distinction between the two components may be required if NORM is regulated as a planned exposure situation (PES). (More about the exposure situation contained the next Section).

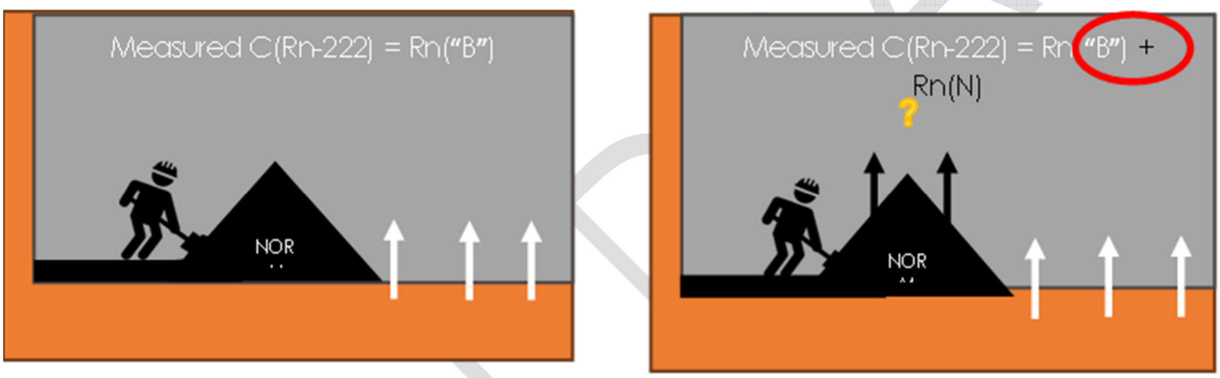


FIGURE 2-15: TWO CONTRIBUTIONS TO THE TOTAL AVERAGE RADON ACTIVITY CONCENTRATION IN NORM INVOLVING WORKPLACES.

Note: White arrows mark the environmental background [Rn(B)], black arrows mark radon concentration related to the NORM involving practice [Rn(N)]

For large ore or waste rock piles, there is a particular case where radon emission shifts from diffusive conditions to advective (or flow through) conditions. This can occur in large rock stockpiles where rock temperatures remain constant, while outside air temperature changes. This results in some stockpiles "breathing". The pressure difference between the bottom and the top is proportional to the temperature difference and can be estimated by using the barometric formula [50]. The temperature difference determines both the intensity and the direction of the soil air flow. Figure 2.16 illustrates the mechanism: if the outside temperature (T_a) is higher than the temperature inside the pile (T_p), then there is a convection flow from the toe to the plateau of the rock pile. Such a situation is typical of the summer season. During the winter season or even in cold summer nights, when T_a<T_p, the soil air convection is reversed.

The convection-induced radon flux can exceed by several orders of magnitude the radon flux from diffusion alone and is directly proportional to the velocity of flow. However, at high velocities of flow, the radon flux is constrained by the emanation factor and the radon generation rate in the porous volume of the pile. On the other hand, in the areas of the waste rock pile where an inflow of air takes place, the ordinary radon flux caused by diffusion may be partly suppressed or strongly diminished.

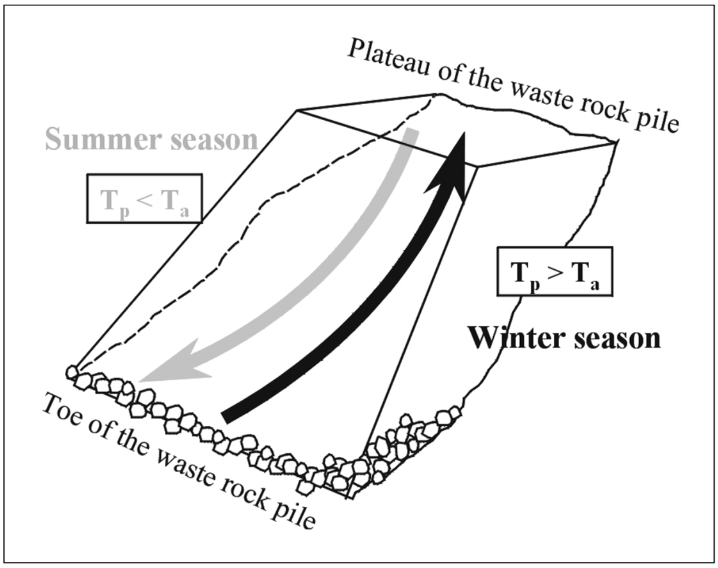


FIGURE 2-16: SCHEME OF THE ADVECTIVE AIR FLOW IN A WASTE ROCK PILE.

Note: T_p – Temperature inside the pile; T_a – temperature outside the pile (from [51])

2.4.5 Radon and the system of protection

In the system of radiation protection, the regulation of exposure to radon depends upon the type of *exposure situation*. Geogenic or naturally occurring radon is commonly considered to be an existing exposure situation (EES). The IAEA [57] distinguishes two categories of workplace that should be considered: above-ground workplaces and below-ground workplaces.

Examples of above-ground workplaces that have touchpoints to NORM involving industries include

- Workplaces where the radon levels might be elevated due to the geological conditions or due to limited ventilation;
- Enclosed raw material production facilities (e.g., processing facilities involving NORM);
- Water treatment facilities;
- Fish hatchery buildings;
- Thermal spas.

Examples of below-ground workplaces are:

- Underground mines;
- Tunnels;
- Basements;
- Underground laboratories;
- Tourist caves;
- Food storage caves (e.g. for production of wine or cheese, for cultivation of mushrooms).

Many countries maintain lists (called "positives" lists) which identify work types that are part of many national regulations.

Later in this handbook, we discuss the differences between planned exposure situations (PES) and existing exposure situations (EES) and it is important to note that there are differences in the way that radon is managed between the two situations.

The general requirements for EES and PES for radon are summarized in Table 2-20.

TABLE 2-20: DIFFERENCE BETWEEN PES AND EES IN RADON MANAGEMENT

	PES	EES
Controls	Occupational: effective dose, from all exposure pathways, to be less than 20 mSv/y. Public: effective dose, from all pathways, to be less than 1 mSv/y. Doses to be optimized (usually through a dose constraint)	Occupational: workplace radon reference level: At highest 1,000 Bq/m³ (ICRP/IAEA) Public (households): At highest 300 Bq/m³ (ICRP/IAEA)
Management	Development, approval, and implementation of a Radiation Management Plan.	The only requirement is "optimization". No additional requirement, except if reference values exceeded.

Reference levels for thoron are generally not established. However, in Cameroon, 500 Bq/m³ is proposed as the reference level for thoron, based on the national survey over 1500 dwellings. By choosing 500 Bq.m^{-3} as the reference value for thoron, 4 % of houses are above this level.

Operations or practices involving NORM where the activity concentrations above the exemption values are sometimes regulated as planned exposure situations (PES). For PES, dose limits apply, and this requirement may result in complexities if it is applied to radon. In such a case, the dose coefficient of radon (see next Section) will result in "high" dose estimates; even though the radon concentration is significantly below the reference value.

A particular challenge may be the determination of the radon component that can be attributed to NORM as the source. A methodical guideline for radon from large contaminated areas, as it occurs in mining, is described in the German Calculation Guideline Mining [34].

2.4.6 How can doses from radon be estimated and assessed?

When measuring radon or radon decay products (and the analogous case for thoron and its decay products), the results for radon are usually compared to reference levels. If the concentrations exceed the reference levels, then an investigation occurs, and action must be taken to reduce the levels. This is the standard way of real-time monitoring and management of radiation exposure.

How do we convert measurements into dose?

There are many methods for doing this, and some are shown below. They are all based on dose coefficients compiled in Table 2-21. Note that national regulations may refer to different dose coefficients (cf. [52]). So, select the dose coefficient in line with the national requirements!

Annual Average Method

- Measure the average annual radon activity concentration in workplaces where workers spend a lot of time.

- If the average radon level exceeds the action/reference level, remedial action must be taken to reduce the radon concentration.
- To assess the individual dose due to radon, a personal passive dosimeter can be used to measure the worker's average radon exposure (WL; Bq h/m^3). This value is then multiplied by the dose coefficient (RDC), which is defined for a working time of 2,000 hours per year and an equilibrium factor of 0.4.

TABLE 2-21: DOSE COEFFICIENTS FOR RN-222, RN-220

Nuclide	Dose coefficient	Exposure conditions	Reference
Rn-222	0.18 nSv/h per (Bq/m^3)	(All)	ICRP 137 [29]
Rn-220 +progeny	1.4 mSv per mJ·h/m^3	Workers	ICRP 65 [53]
	5 mSv per WLM		
	9 nSv per Bq h/m^3	for members of the public	UNSCEAR 2000 [54]
	3 mSv per mJ·h/m^3	underground mines and in buildings	ICRP 137 [29]
	10 mSv per WLM		
	13 nSv per Bq h /m^3	Indoor workplaces	
	15 nSv per Bq h /m^3	Tourist caves	
	6 mSv per mJ·h/m^3	indoor workplaces with substantial physical activities, and for workers in tourist caves	
	20 mSv per WLM		
Rn-220 +progeny	1.5 mSv per mJ·h/m^3	all situations of occupational exposure	

More detailed method for radon alone:

- Determine an exposure work group that you need to assess doses for - for example, workers in a factory that handle mineral sands.
- Consider the exposure situation – for example, is the whole of the work group being exposed to the same sources, or are there particular subgroups of workers who have a different exposure? This will require some judgment, so ensure you have evidence to support your decision.
- Determine the average radon concentration that the workgroup is exposed to – for example, the monthly average in the workplace is 150 Bq/m^3 of radon.
- Determine the exposure hours – usually in a month, workers will work up to 200 hours.
- From this, you can calculate the exposure, which is 150 Bq/m^3 x 200 h = 30,000 Bq·h/m^3
- Multiplying the exposure by the relevant dose coefficient according to Table 2-21. (Note that there are a couple of different dose coefficients, so select the dose coefficient in line with the national requirements!)

More detailed method for radon decay products.

- As above, determine an exposure work group that you need to assess doses for - for example, workers in a factory that handle mineral sands.

- As above, consider the exposure situation – for example, is the whole of the work group being exposed to the same sources or are there particular subgroups of workers who have a different exposure? This will require some judgment, so ensure you have evidence to support your decision.
- Determine the average radon decay product concentration that the workgroup is exposed to – for example, the monthly average in the workplace is 0.15μJ/m^3 of radon decay products.
- Determine the exposure hours – usually in a month, workers will work approximately 200 hours.
- From this, you can calculate the exposure, which is 0.15 μJ/m^3 x 200 h x 1.2 m^3/h = 36 μJ·h/m^3
- Multiplying the exposure by the relevant dose coefficient according to Table 2-21. (Note that there are a couple of different dose coefficients, so again, select the appropriate coefficient and provide evidence of your decision.)

It is very important to ensure that when conducting dose assessments, a representative number of samples is taken. It is not usual to make a dose assessment based on a single measurement. Several studies over the last decades have demonstrated the variability of aerosol conditions in different types of workplaces, as well as the variability of radon and radon progeny concentrations (summarized, for example, in ICRU Report 88 [55] and ICRP Publication 137 [29]).

While radon progeny is the primary source of health risk, national legal frameworks and international recommendations addressing safety standards primarily refer to radon activity concentration measurement, rather than equilibrium equivalent activity concentration or potential alpha energy concentration. The reason is that under "*a range of aerosol conditions normally encountered*" the radon gas concentration is a good proxy for the dose. Radon gas concentration measurement is less complex compared to the measurement of radon progeny. In cases of forced ventilation and specific aerosol conditions, radon gas concentration measurements should be replaced with radon progeny measurements.

2.4.7 Which methods are suitable for controlling radon?

For radon, exposures in open air are unlikely to be a concern. For particular cases, e.g. if large heaps/stockpiles with uranium-radium contamination, this should be confirmed with monitoring. For enclosed spaces, where radon-emitting material is handled, stored or processed, then radon concentration may need to be controlled. Radon or radon decay product concentrations should also be measured in the underground workplaces and workplaces where underground water is processed.

The best method for radon control is to try to prevent it from entering the atmosphere by installing barriers; however, this can be complex. The most used control for radon is to provide sufficient ventilation to ensure that radon concentrations are at an acceptable level. Ventilation can take many forms, from active air movers to passive roof ventilators.

Sensible placement of material emitting radon should be part of workplace design. For example, storing radioactive materials near heavily occupied work areas should be avoided if possible.

It is relevant to take an integrated approach and recognize that general air quality requirements mean that it is usual to have ventilation for all enclosed spaces, buildings, and sheds. Therefore, the task is then to ensure that the ventilation capacity is also sufficient for radon control. This may require some calculations of possible airborne concentrations and target concentrations. Usually, this will result in the “air changes per hour” that are required to keep all airborne contaminants under control.

For underground mines, there are specific ventilation needs that need to be adhered with. Some good practices for underground mines include:

- A minimum air-flow of 10 m^3/s in all drives.
- A one-pass ventilation system, with no re-use of ventilation air.
- Continuous ventilation of all drives.

Another good practice for all workplaces is to design the workplace so that airborne contaminants are controlled, either at their source or through adequate ventilation.

The examples above are for radon.

The methods are also applicable for thoron and thoron decay products, noting the different dose coefficients (Table 2-21).

2.4.8 Summary and practical tips

Radon can be a complex subject for practitioners. However, it does not need to be difficult if the practitioner has a good understanding of the basics of radiation protection and monitoring. There is no need to make the situation more complex than it needs to be.

The key points to remember are:

- The noble gas radon does not lead to a significant dose (Table 2-21). The majority (>95%) of the dose associated with radon comes from its short-lived decay products.
- Radon provides a way for radon decay products to move in the atmosphere
- A key to radon is characterization, which can be done only through measurement.
- There are many methods to measure radon and its decay products. Make sure you understand what you are measuring and why you are measuring.
- If you measure radon, you have to think about equilibrium, attached fraction/unattached fraction.
- If you measure radon, you have to think about its variability - temporal and spatial. Longer measurements are typically necessary to collect enough data for a proper description of the situation. It is important to use metrologically verified detectors/monitors.

When considering radon exposures and risks for industries with NORM, it is important to remember that exposures can occur for both workers and members of the public.

When risks must be reduced, ventilation is one simple method for controlling radon through dilution. However, it may not be sufficient in specific cases. More efficient methods include controlling the radon at its source.

2.4.9 How to get further information?

General Textbooks:

M. Baskaran: Radon: A Tracer for Geological, Geophysical and Geochemical Studies. Springer Geochemistry. ISBN 978-3-319-21328-6 ISBN 978-3-319-21329-3 (eBook). DOI 10.1007/978-3-319-21329-3. Springer International Publishing Switzerland 2016

WHO Handbook WHO handbook on indoor radon: a public health perspective / edited by Hajo Zeeb, and Ferid Shannoun. ISBN 978 92 4 154767 3 (NLM classification: WN 615). World Health Organization 2009

TOXICOLOGICAL PROFILE FOR RADON. U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES. Public Health Service. Agency for Toxic Substances and Disease Registry. May 2012

Specific publications

RadoNORM Project Publications, e.g. [56]

IAEA on Radon in Workplaces [57]

R. Trevisi, et al. on regulatory approaches to assessing workers' exposure to radon in industries involving NORM [58]

3 NORM in Industries

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Contributors: Phillip Egid, Oskar van Dongen, Fidel Grandia, Rosabianca Trevisi, Katerina Rovenska

3.1 Introduction

Naturally occurring radioactivity is ubiquitous, occurring everywhere. In all mining operations and minerals processing operations, naturally occurring radionuclides are present through the varying levels of naturally occurring uranium and thorium in the geological formations and ores produced. The concentrations of uranium and thorium, and their respective decay products in industrial processes depend on the mineralogy of the ores and geological formations, and on the chemical and physical processes used.

The processes in real industry are complex systems with many intertwined processes, and a generic flow scheme of modern production chains is given in Figure 3-1. This simple flow scheme illustrates some typical properties of NORM-related processes.

The scheme shows that the origin of all NOR, which generate NORM, is mining or other extraction of natural resources. Mining is the extraction of valuable geological materials and minerals from the surface of the Earth (Wikipedia). Mining includes many different techniques (mainly mechanical and hydraulic) and also includes resource recovery or extraction. It is this primary step of production that introduces a certain amount of radioactivity into the process chain.

Processing 1 [P1] refers to the onsite treatment of minerals or ores resulting in "concentrates" as an outcome (also known as "beneficiation"). In oil and gas production, this step is the on-site separation of waters from hydrocarbons such as crude oil.

In the **processing 2**-step **[P2]**, pure metals, specific minerals, or basic substances are produced. Typical processes are smelting or hydro-chemical processing. In the oil and gas industry, this is the refining of hydrocarbons, such as crude oil, into useful products like LPG, gasoline, kerosene, and fuel oil.

Generally, the products of Processing 2 are ready-to-use final products, but often further processing is required.

In almost all industrial processes, the initially introduced radioactivity is removed from the main product and transferred to waste or by-products after processing 2. One exception is the processes by which uranium is transferred into the product, for example, into phosphoric acid (see Section #&). Other, more exceptional cases, include the deliberate manufacture of uranium or thorium, respectively, as pure chemical compounds or even as metals.

In **processing 3 [P3] and 4 [P4]**, materials are generally low in radioactivity, and no special radiation protection measures are required. However, NORM may be used as auxiliary (operating) materials. Typical examples are refractory materials. Because of their use in coal-fired power plant boilers or rotary kilns for cement production, these two sectors have been classified as relevant to radiation protection. Other examples include thoriated electrodes and potassium salts. Such cases will be described in Chapter 10 on consumer products. Figure 3-2 gives an example of the application of the scheme shown in Figure 3-1.

An example of an industry that does not fit in the chain is geothermal energy production. Here, NORM is only generated as waste.

In practice, the real production chains are more complex than the simple linear scheme of Figure 3-1 is shown in Figure 3-2. Nevertheless, the classification of the processes in Figure 3-1 gives a structure for considering industries involving NORM for radiation protection purposes.

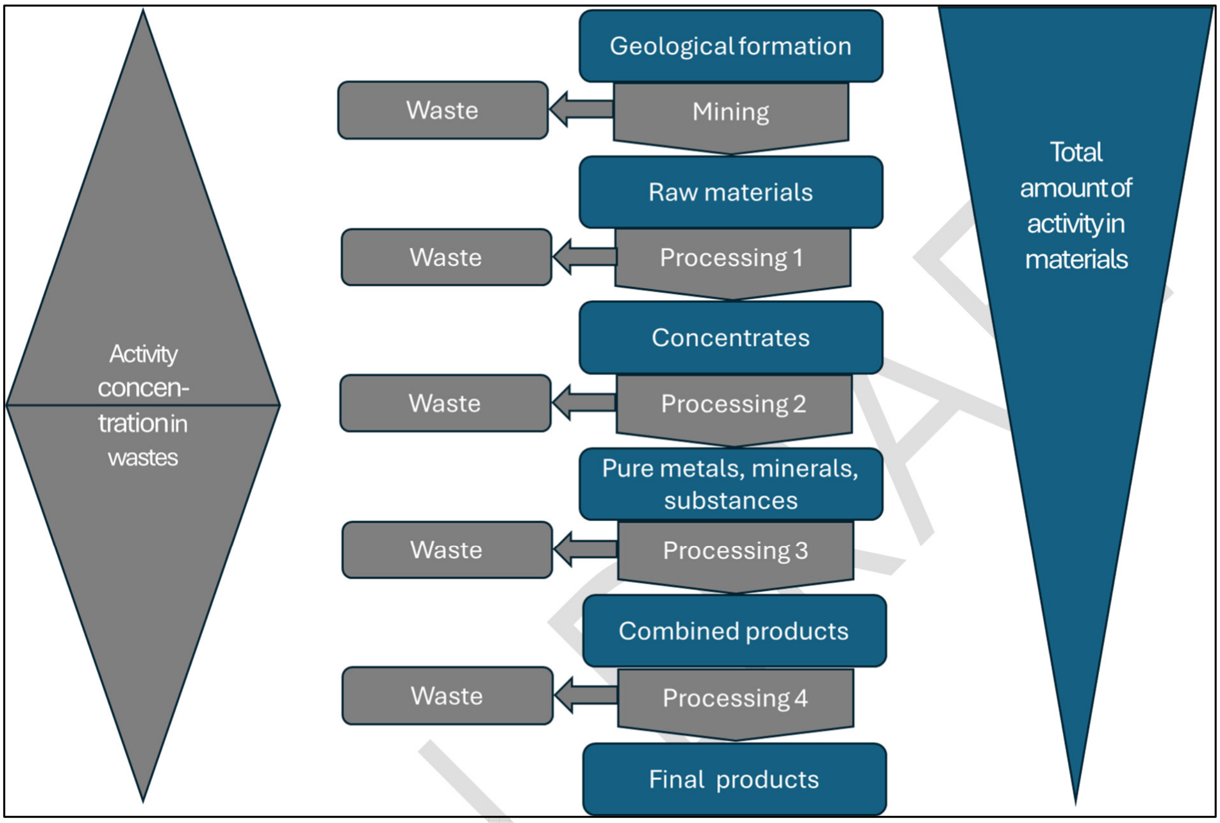


FIGURE 3-1: GENERIC FLOW SCHEME OF PRODUCTION CHAINS

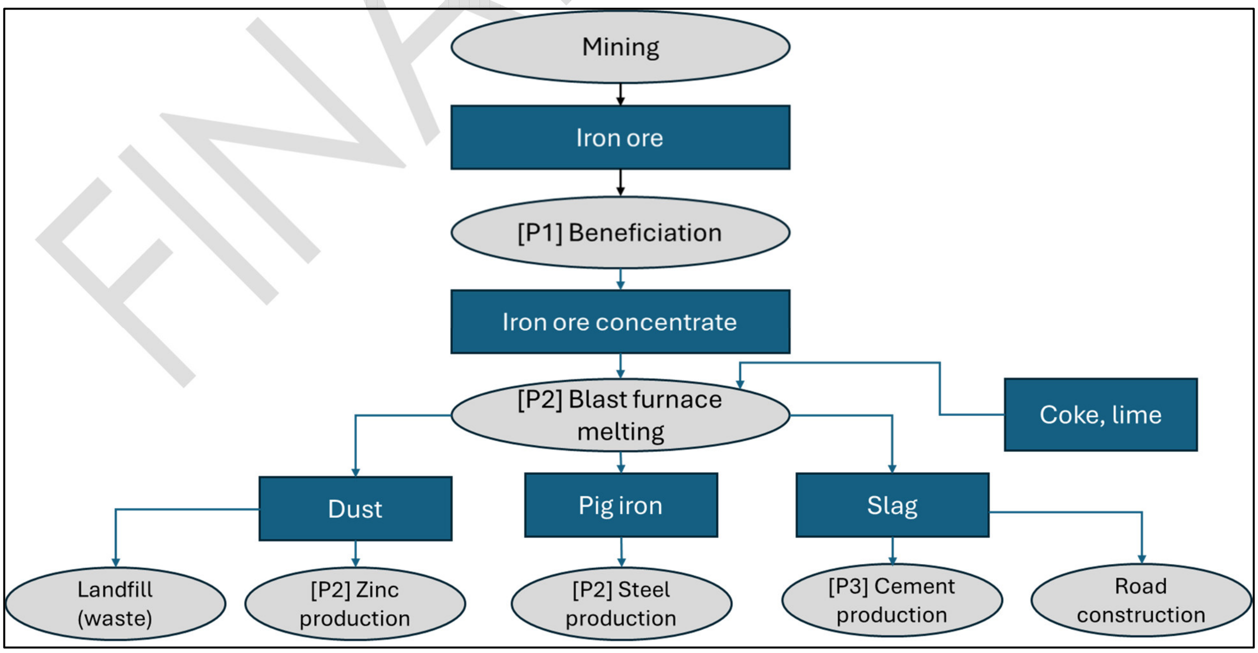


FIGURE 3-2: DETAILED FLOW SCHEME OF STEEL PRODUCTION

In the following sections, an overview of where NORM can be found in mining and industries is provided. This knowledge is helpful for the following reasons:

- identification of the industrial sectors and materials of concern for regulatory purposes,
- awareness for operators about potential radiological issues in their plant, including situations where there may be unintentionally contaminated components,
- management of radioactively contaminated raw materials, NORM wastes, by-products, or products from normal operations,
- management of radioactively contaminated wastes from decommissioning operations,
- identification of workplaces of interest for radiation protection purposes.

A special case is K-40, which occurs in potassium salts and is widely used in many industrial processes, including food and feed production. Some information about K-40 is given in Section 3.10.4. Potassium salts in consumer products are one topic in Chapter 10.

3.2 Which industrial sectors involve NORM?

This handbook is about radiation protection in industries involving NORM. These industries are impacted by the unintentional radioactivity in the substances they process, leading to the need for radiation protection.

As part of the processing of NORM, many companies also use radiation sources containing (mostly) man-made radionuclides, for example, to monitor tank levels. In some cases, the radiation sources may contain natural radionuclides such as Ra-226 or Po-210. These sources have long been subject to established radiation protection measures and are not covered in this handbook. International standards for sources, for example, are IAEA GSR 3 [5].

A first overview of "Technologically enhanced exposures to natural sources" was published in the UNSCEAR Report from 1977 [59]. In this report, UNSCEAR reported on the use of building materials, use of phosphate fertilizers, coal-fired power plants, and use of natural gas "for kitchen ranges and space heaters" and the resulting potential exposure to radon. Since then, safety improvements, scientific studies, and industry experience has broadened the view and, combined with the gradual lowering of limits, has led to the system of radiation protection being extended to include NORM.

Since industrial operators, in many cases, process natural radionuclides unintentionally in their facilities, so-called "positive lists" are used in many countries to identify industries or practices where radiation protection is necessary for NORM. Positive lists for industrial sectors identified by ICRP and IAEA are given in Table 3-1. The industries listed are assessed to be likely to require some form of assessment and regulation. The ranking in the table is roughly in descending order of radiation protection priority.

By considering the groups of typical processes, it can be seen that NORM mainly occurs in processing step P2 (8 times). [P3] and [P4] differ from [P1] and [P2] in one fundamental aspect. While in [P1] and [P2] radioactivity is unintentionally present in the processes, and the decision on radiation protection must be made based on the respective situation, in [P4], (for example where refractory materials are used as auxiliary (operating) materials or, like thorium, are intentionally added in tungsten), it is usual to assume that there is sufficient knowledge of radioactivity. The same applies to the use of abrasives or even potassium salts in the processes classified as [P3]. These examples show that just using the familiar ICRP definition that exposure to NORM is an Existing Exposure Situation is not always the case for some industries.

[Tip: A common theme in this Handbook is to encourage the reader to think about the situation in hand, rather than simply following established practices. NORM is complex and requires a good understanding of many processes.]

TABLE 3-1: IAEA AND ICRP CLASSIFICATION OF INDUSTRIAL SECTORS REGARDING REGULATORY CONSIDERATION AND TYPICAL NORM-RELEVANT PROCESSES. PROCESSING STEPS ACCORDING TO SECTION 3.1, ABBREVIATED [P1] – [P4]

IAEA SRS 49	**ICRP 142**	**[Processing step] Typical NORM-relevant processes**
Extraction of rare earth elements	Extraction of rare earth elements	Mining (mechanical extraction), **[P1]** beneficiation
Production of thorium and its compounds	Production of metallic thorium and its compounds[7]	**[P2]** Multi-step chemical processing (hydrometallurgy)
Production of niobium and ferro-niobium;		**[P2]** Pyrometallurgy of concentrates
Use of thorium and its compounds	Use of metallic thorium and its compounds	**[P3]** Production of alloys (thoriated tungsten, thoriated magnesium) by sintering; mechanical processing of alloys **[P4]** Use of thoriated electrodes in consumer goods.
Mining of ores other than uranium ore	Mining and processing of ores [8]	**[P1**] Mechanical extraction of ores; beneficiation
Production of oil and gas	Oil and gas recovery process	**[P1]** (Liquid mining) NORM in hydrocarbons and in produced water
Manufacture of titanium dioxide pigments	Manufacture of titanium dioxide pigments	**[P2]** Chemical processing (hydrometallurgy)
The phosphate industry	The phosphate mining and processing industry	**[P2]** Chemical (hydrometallurgical) processing. High temperature treatment for P-acid production
The zircon and zirconia industries	The zircon and zirconia industries	**[P2]** Chemical (hydrometallurgical) processing. High temperature treatment (fusing, sintering)
Production of tin, copper, aluminum, zinc, lead, and iron and steel	Production of metal (tin, copper, iron, steel, aluminum, niobium/ tantalum, bismuth, etc.)	**[P2]** Chemical processing (hydrometallurgy); sintering and melting (pyrometallurgy)
Combustion of coal	Combustion of fossil fuel (mainly coal)	**[P2]** Transformation of carbon into gaseous CO_2 (enrichment of non-volatile elements in ash)
Water treatment	Water treatment	**[P2]** Sorption and precipitation of trace components
	Geothermal energy production	(Liquid mining) NORM in accompanying production water

[7] (i.e. for their metallic, not fissile or fertile, radioactive properties).
[8] (other than uranium or thorium for the nuclear fuel cycle).

	Cement production and maintenance of clinker ovens	**[P3]** (Mixing of products from [P2]). NORM in demolition wastes from the decommissioning of refractory units
	Building materials (including building materials manufactured from residues or by-products)	**[P3]** Mixing of mineral components.

Note that while uranium mining and extraction are technically NORM-related processes, they are usually strictly regulated in all countries where such mining occurs. Regulatory systems in accordance with IAEA requirements mean that all facilities processing uranium are usually considered planned exposure situations, requiring licensing and radiation management plans.

Uranium mining and processing is mentioned in this handbook for the sake of completeness but will not be considered separately. There are many other excellent guidelines on this. (For example [60]).

Experience from several projects and investigations has shown that NORM also occurs in other sectors not covered in Table 3-1. The European project RadoNorm [61], identified the following additional industrial sectors :

- Mining of Th ore,
- Heavy mineral sand ore processing, total heavy mineral concentrate (THM) production
- Titanium metal smelting and refining
- Other metal (not directly mentioned in the list) mining and processing
- Bauxite and aluminum industry
- Refractory brick production and use
- Abrasives production and use
- Pulp and paper mills and primary paper production
- Coal mining and processing
- Scrap recycling (cleaning, melting, and recovery of mercury) and disposal of residues from recycling
- Underground workplaces other than mines, such as tunnelling, touristic routes, caves
- Radon spas
- Use of geothermal waters or minerals (sediments) in health and cosmetic treatment
- Building and construction industry
- Legacy sites involving NORM
- High natural background radiation areas (HBRA)[9]

Due to technical developments, new processes may occur that are not covered in the lists. For instance, experiences and literature indicate that NORM may also be present in:

- Biotechnological processes and incineration installations as radium-bearing deposits [62],
- Installations for the bleaching of Fuller's earth as radium-bearing deposits,
- Aerosols or dust from the baking of electrodes for electric furnaces with temperatures between 900°C and 1100°C, involving high concentrations of Po-210.

[9] HBRA are a special field in RP. They are not considered NORM in this handbook. For some challenges related to HBRA see Chapter 2.3.9.

- Medical diagnosis and treatment using natural radionuclides (also known as theranostics).

The RadoNorm-Project developed an approach, assuming an initial position of limited knowledge of the situation. The strategy was based on the assumption that all industries that involve mining or processing raw resources are likely to encounter NORM. The RadoNorm approach proposes several tiers for determining the NORM inventory in existing processes, and also from legacies of former processes, based on the following [61]:

I. Analysis of the presence of natural mineral resources (the content of NOR is an inherent feature of all materials of mineral origin).

II. Identification of ongoing and any former mining industries (including other underground workplaces).

III. Identification of ongoing and former mineral and fossil fuel processing industries

IV. Analysis of commodities and products life cycle, including their application, final disposal, and secondary wastes generated.

A matrix showing the tiers and their relation to different types of materials is shown in Figure 3-3.

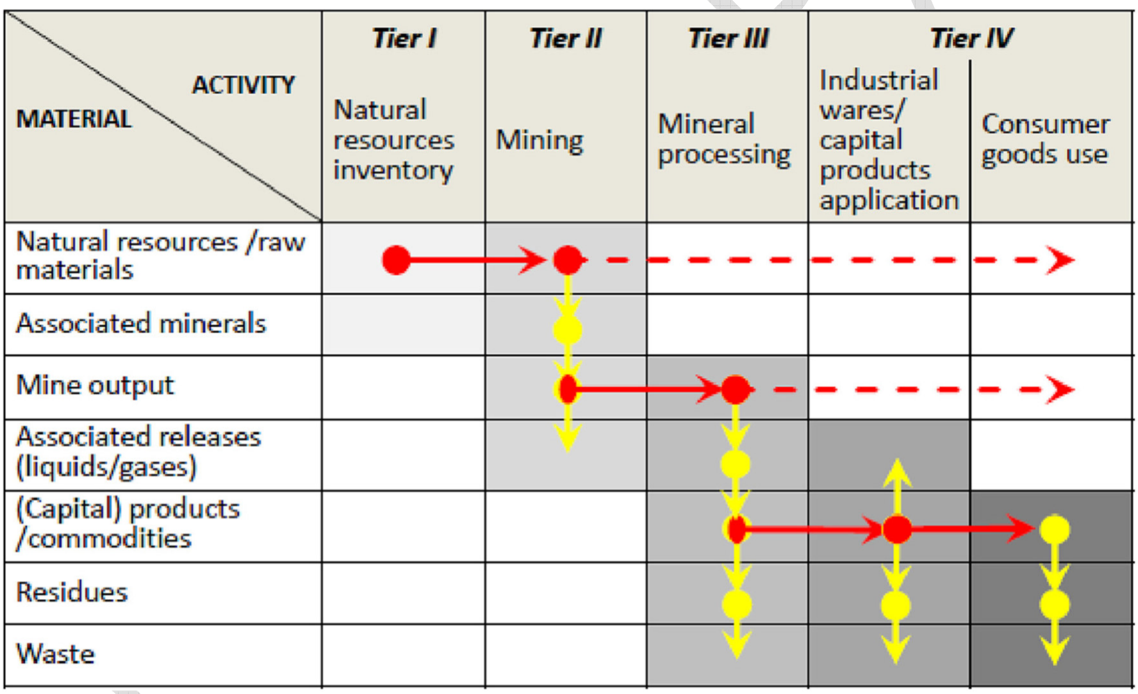


FIGURE 3-3: MATRIX OF NORM IDENTIFICATION TIERS (FROM [61])

In their paper [61], Michalik et. al. state: *The first tier aims to provide general information to support the identification of potential NORM exposure situations and the consideration of potential radiation exposure-related problems at the level of industry design and strategy for the exploitation of mineral resources in a country, prior to the start of any exploitation. Working through remaining tiers (II, III and IV), at a theoretical level, can inform on possible exposures that could arise and support the development of any necessary prevention or mitigation methods in advance for all aspects of the life cycle of a planned commodity or product. It is* *important to note that, when natural resources have not yet been exploited, any existing exposure should be considered as natural background.*

The RadoNORM is a practical and useful starting point for countries new to the NORM area.

Even though potassium salts frequently exceed the K-40 exemption value of 10 Bq/g, potassium salt mining or processing has not generally been considered an industry involving NORM until recently.

3.3 How can the relevant materials be identified?

The Positive Lists of Table 3-1 are mainly intended to support regulators. The lists do not provide details on where NORM occurs in a process and where it does not.

For a company that operates a facility that belongs to one of the industry sectors mentioned in Table 3-1 the following questions could be considered:

- What information do we have on the primary radiological characteristics of the materials being processed, the final products, the auxiliary materials and the wastes?
- What information do we have on the processes that may result in concentrating of radionuclides?
- Where do we expect NORM in our systems?
- How can we influence the occurrence of NORM? Can it be avoided or reduced and if so, how?
- Which material flows in the overall process are affected? Does this concern products, waste, or discharges?
- How dangerous is the radioactivity for the employees in the company (or maintenance personnel temporarily working in the company) or for the environment, especially for members of the public?
- What are the regulatory requirements?
- How can we comply with the regulatory requirements with appropriate efforts?

In addition, bearing in mind the goals of sustainability and a circular economy, the following question should be asked:

- How does recovery and recycling affect the radioactive contamination of processed materials in a particular industry or facility?

To answer these questions in an individual case, the following knowledge is useful:

1. How do typical processes change the radionuclide composition of NORM?
2. How do typical processes affect the radionuclide concentration in NORM?
3. How can we quantify the radiation risks and compare them with the regulatory requirements or with broadly accepted international standards?

3.4 How can industrial processes be characterized?

Industrial processes are usually complex, multi-step processes that alter the composition of the materials being processed. Their general aim is to produce an output that is valuable to society. An example from the phosphate industry that shows the complexity of real processes is shown in Figure 3-4. The two process steps are typical for the general process steps [P1] and [P2] described in Section 3.1.

To find out where NORM occurs and where it is concentrated or diluted by a process, each process step should be considered. This can be done through a simple material balance model. A generalized flowchart showing the basic steps of industrial processes is shown in Figure 3-5 and can be used as a starting point for considering NORM in mining and industrial facilities. Some explanations of terms are given in Table 3-2. Note that the term "waste" is used here for all output materials that are not the "product" of the process. Besides the actual waste, the term "Waste" in Figure 3-5 can stand for a marketable by-product or an output that is reused in the process itself, as shown in Figure 3-4. This is sometimes referred to as a "residue".

It must also be noted that not all process steps include all elements shown in the flowchart. For instance, drying or dewatering sludge does not require input materials (apart from energy). A particular complexity occurs when "waste" is reused in a recycling process (for example, to improve recovery). Nevertheless, a simplified scheme is helpful for analyzing complex systems. Its application will be described in Section 3.10.

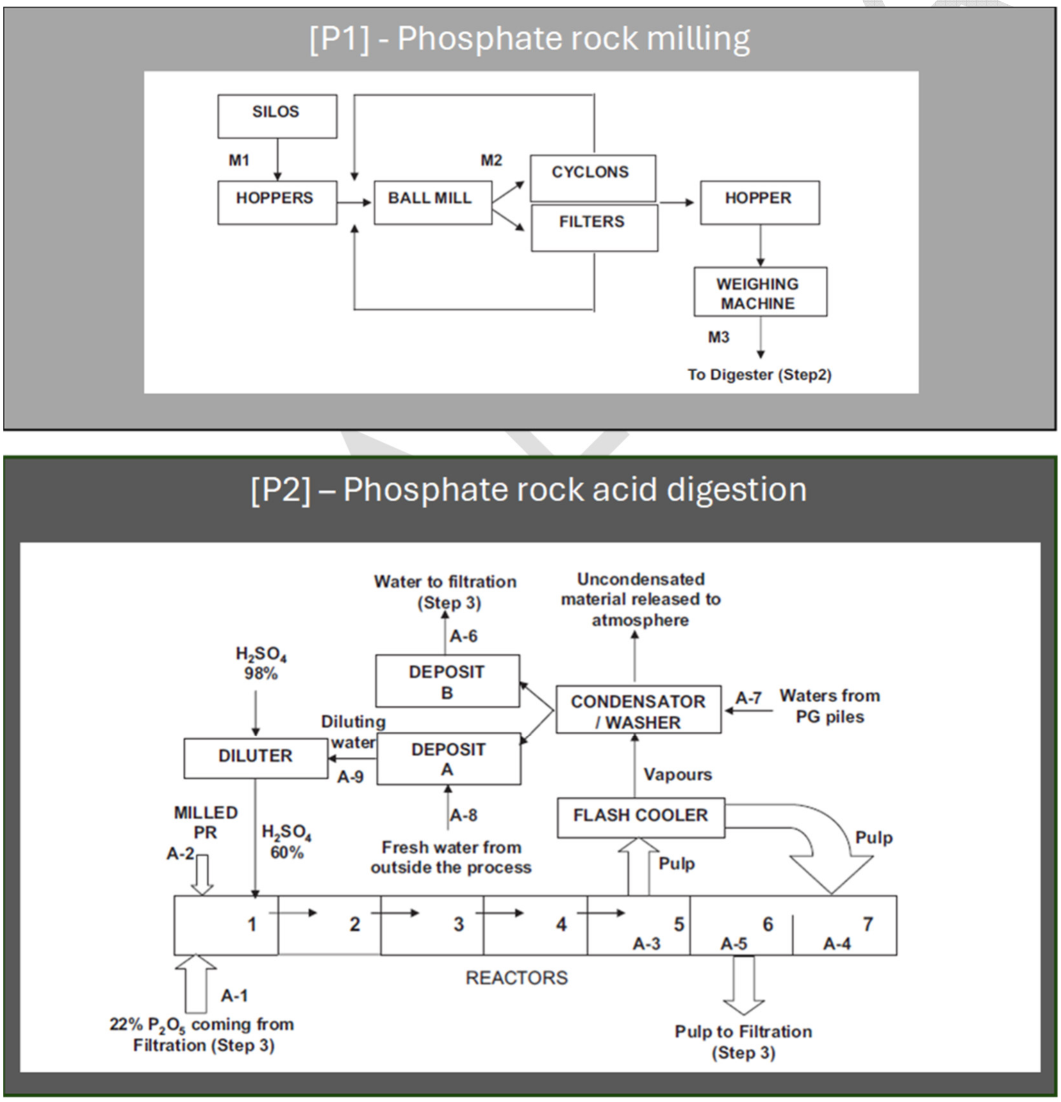


FIGURE 3-4: TWO PROCESS SCHEMES OF A PHOSPHORIC ACID PLANT

Picture taken from Bolivar et al. [67]

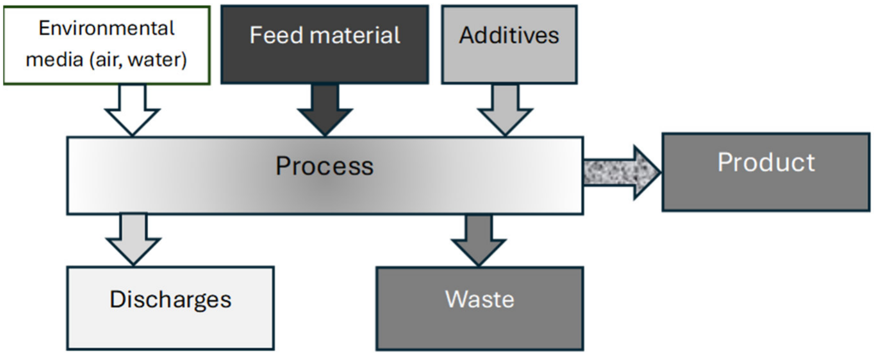


FIGURE 3-5: GENERALIZED FLOWCHART OF INDUSTRIAL PROCESSES.

Grey-tones indicate mass streams that may contain radionuclides.

TABLE 3-2: EXAMPLES OF PROCESSES AND MATERIALS AND THE TERMS USED

	Beneficiation	**Hydrometallurgy**	**Pyrometallurgy**	**Oil production**
Raw material/ Feedstock material	Minerals, ores	Mineral or ore concentrates	Mineral or ore concentrates	Natural hydrocarbons
Additives	Surfactants (for floatation)	Acidic or alkaline solutions	Coke, lime, slice, etc.	(non)
Utilized environ-mental media	(fresh) water	(fresh) water	Air	
Processes	Mechanical or hydraulic separation (e.g. sieving, milling, flotation)	Chemical reactions (dissolution, precipitation, sorption, …)	Smelting at high temperatures	Separation of phases (water-oil).
Products	Mineral concentrates	Purified or concentrated compounds	Metals	Crude oil
By-products and wastes	Mineral residues (tailings, heaps)	Various residues (gypsum, sludges, …), partly depo-sited in facility components	Slag, filter dust	Sludge, scales
Discharges	Processed water	Processed water (once neutralized)	Processed air	Produced water

3.5 What do we know about mining products?

3.5.1 How do ores and minerals differ in their radionuclide composition?

As described in Section 3.1 the primary source of NOR in industrial processes is mining[10]. Therefore, any assessment of NORM in industrial processes should start with a knowledge of the radionuclide composition and the ranges of activity of the raw materials.

The relevant radionuclides in NORM are (except for K-40) the radionuclides of the U-238 and Th-232 decay series. In exceptional cases, radionuclides of the U-235 decay series (in particular Ac-227) may also be relevant. For the characterization of NORM, the long-lived radionuclides are usually sufficient since short-lived daughter nuclides quickly grow into equilibrium with their long-lived predecessors or decay until equilibrium with them is reached (cf. Section 2.2.4).

Indicative radionuclide data in raw materials ("Type M1" according to Section 2.2.8) for the industrial sectors mentioned in Table 3-1 are shown in Table 3-3. The activity concentration will be discussed in Section 3.10.

It should be noted that the radionuclide composition of ores or minerals is only one factor that influences the generation of NORM in industrial processes. Mineral composition and chemical forms also play an important role, however detailed consideration of these factors are beyond the scope of this handbook.

An examination of published data in international journals, proceedings, and reports, shows that most studies focus on only a few radionuclides. Information on the data of Th-232, U-238, or Ra-226 is typical. The standard method of measurement is gamma-spectrometry. It is important to note that gamma spectrometry does not directly measure U-238, Th-232, or Ra-226. This is because the method measures the decay-product gamma lines of Ac-228 (for Ra-228), Pb-212, Tl-208 (for Th-228), and Pb-214, Bi-214 (for Ra-226), and assumes radioactive equilibrium in the decay chains (see Chapter 5). Such incomplete analyses provide an insight into the general composition pattern but may result in an underestimation of doses (see Chapter 5).

Data records that provide a comprehensive analysis of all long-lived radionuclides are seldom available. They would provide details of the status of radioactive equilibrium in the decay chains of most ores and minerals. Chapter 5 provides a method for determining the activity concentration of the non-detected radionuclides from the detected ones through an understanding of the material (see "indirect determination" in Chapter 5).

However, as a starting point, it is usually acceptable to assume radionuclide equilibrium for materials that are unaffected by chemical or thermal processes.

[10] Natural oil and Gas production are specific forms of liquid mining. Groundwater extraction for drinking water production can also be considered a form of mining. The processes related to these sectors are described in Section 3.6 and 3.7.

TABLE 3-3_ NORMALIZED RADIONUCLIDE COMPOSITION OF RAW MATERIALS THAT ARE EXTRACTED OR PROCESSED IN THE INDUSTRIAL SECTORS RELEVANT TO NORM

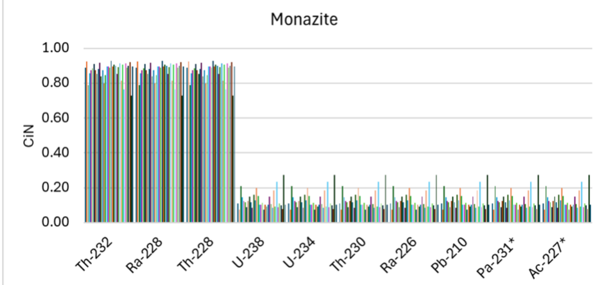
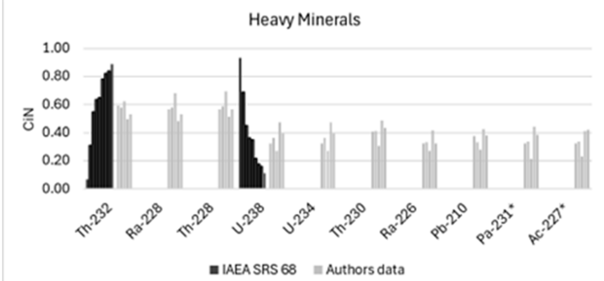
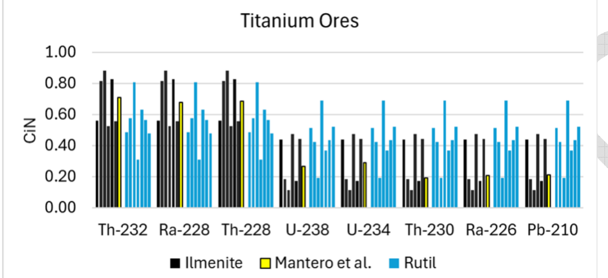
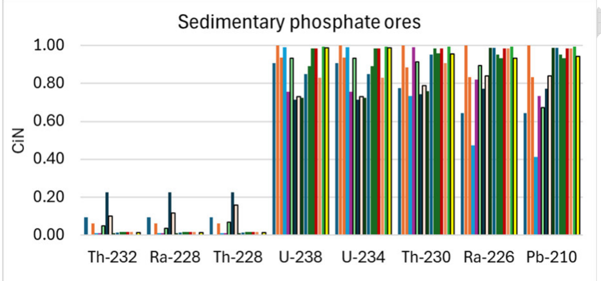
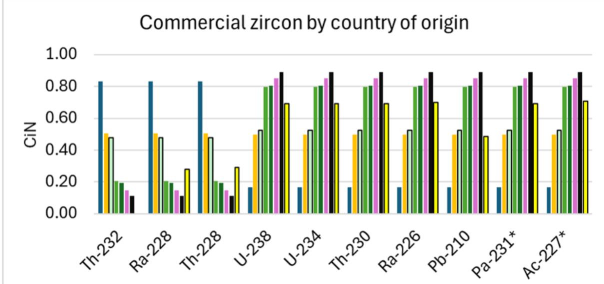
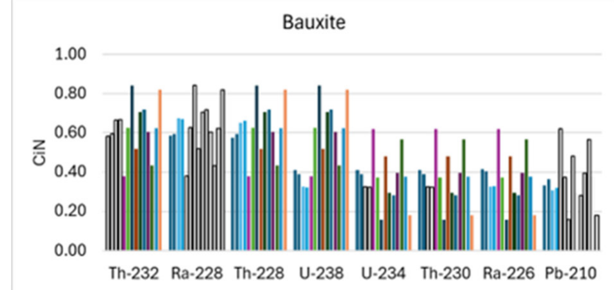
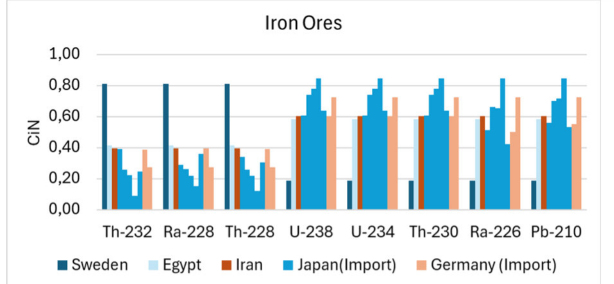
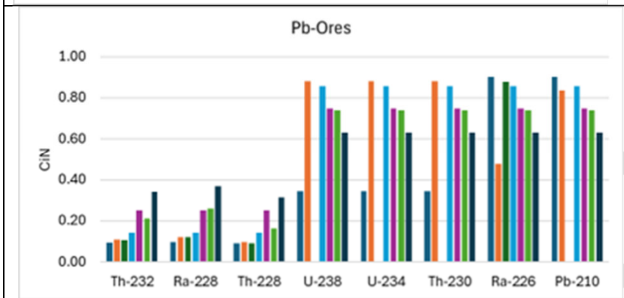
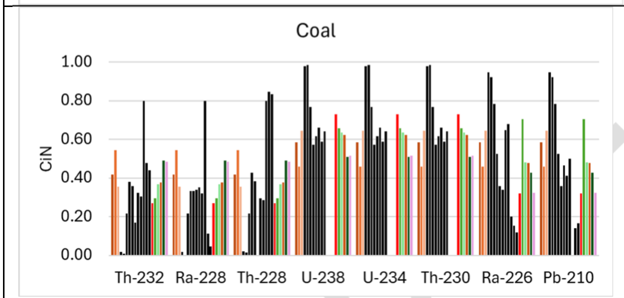
<table>
<tr><th>Diagrams with normalized radionuclide composition in raw materials</th><th>Industrial sectors according to IAES SRS 49 and comments on data</th></tr>
<tr><td>
</td><td>Extraction of rare earth elements: Monazite. Data from IAEA SRS 68 [63]. Summary of published results from Australia, Brazil, India, Korea (N), and of unspecified origin. Radioactive equilibrium assumed.
As expected from mineralogy, Th-232 dominates (with one exception).</td></tr>
<tr><td>
</td><td>Extraction of rare earth elements: Heavy Mineral Sands. Data from IAEA SRS 68 [63]. Summary of published results from Australia, Brazil, India, Vietnam, and Bangladesh, supplemented by unpublished data from authors with extended radionuclide analysis. Data confirm $C_{Th\text{-}232} > C_{U\text{-}238}$ and the secular equilibrium in the decay chains.</td></tr>
<tr><td>
</td><td>Manufacture of titanium dioxide pigments. Data from IAEA SRS 76 [64]. Summary of published results for ilmenite and rutile from different countries, supplemented by data from Mantero et al. [65]. Data Mantero et al. confirm the secular equilibrium in the decay chains. In most cases, $C_{Th\text{-}232} > C_{U\text{-}238}$ holds (in ilmenite more than in rutile).</td></tr>
<tr><td>
</td><td>The phosphate industry.
Data for sedimentary phosphate ores from IAEA SRS 78 [66]. Summary of published results which contain values for Th-232 from different countries, supplemented by data from Bolivar et al. [67]. Data from Bolivar et al. confirm the secular equilibrium in the decay chains, as also assumed in other cases.</td></tr>
<tr><td>
</td><td>The zircon and zirconia industries.
Data from IAEA SRS 51 [68]. Summary of published results for commercial zircon from different countries, supplemented by unpublished data of the authors.
Radioactive equilibrium assumed. Due to high temperature treatment, Pb-210 may be depleted.</td></tr>
</table>

Table 3-3 (continued)

	**Mining of ores other than uranium ore: Bauxite.** Bauxite is used for aluminum production but also for the manufacture of corundum (an abrasive). Data for Ra-228, Th-228, U-238, Ra-226, and Pb-210 from [69], other data from [70]. Radioactive equilibrium assumed.
	**Mining of ores other than uranium ore. Iron ores.** Iron ores have low activity concentrations. Available data from [71], [72], [73] refer to Th-232 and U-238. Data from Japan [74],[75] demonstrate radioactive equilibrium in the decay series. Only in ores from Kiruna (Sweden) Th-232 dominates.
	**Mining of ores other than uranium ore. Lead ores.** Lead ores have low activity concentrations. Data were taken from unpublished data of the authors. They represent ores and concentrates from worldwide producers. Radioactive equilibrium assumed.
	**Combustion of coal** The diagram represents published nuclide compositions of coal. Data were taken from [76], [77], [78], [79]. Activity equilibrium assumed. While the activity concentration in coal is usually very low, uranium-rich coals with $C_{U\text{-}238} >> C_{Th\text{-}232}$ are known in local deposits.

3.5.2 What can be said about water?

Mining affects water in many ways. Large quantities of water are extracted and discharged for the drainage of underground and open-cast mines. Water is also extracted as a by-product during the extraction of crude oil, natural gas or geothermal energy from deep geological formations. In addition, water is used in on-site processing, e.g. as process water in flotation.

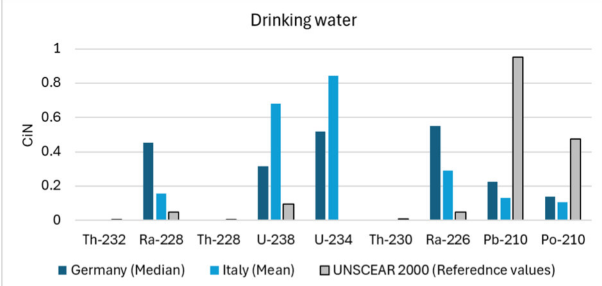
Regarding the radioactivity, three basic types of water can be distinguished.

- Weakly mineralized waters (freshwater) are typical of surface near groundwater. The composition of these waters is determined by the mineral composition of the aquifers, neutral pH (6.0 – 7.5), variable redox potential (Eh), and low temperature (< 30°C), and varies greatly.
- In deep geological strata, mineralization increases and the Eh value decreases (reducing conditions). Typically, such strata contain chlorine-rich brines.

- Many rocks and ores contain sulfides like pyrite. As mining breaks the rock and creates access routes for air, the sulfides oxidize, forming sulfuric acid. This results in acidic mine water, in some cases, with pH values below pH 2.

These three types of water have typical radionuclide compositions that are shown and described in Table 3-4.

TABLE 3-4_ NORMALIZED RADIONUCLIDE COMPOSITION OF DRINKING WATER AS REFERENCE, STRONG ACIDIC WATER OF A MINING AREA, AND BRINES

<table>
<tr><td>


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Freshwaters have a neutral or very slightly acidic pH (6.0 -7.5). The data taken from [80], [81], [82] demonstrate that uranium, radium, Pb-210, and Po-210 in such (drinking) waters occur in varying activity ratios. <u>Typically, thorium isotopes occur only at a negligible level.</u>

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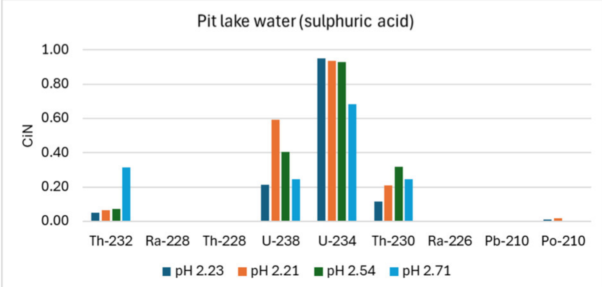

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The compositions of the four pit lake waters shown in the diagram are examples of strongly **acidic mining waters** (Data from [83]), pH 2-3). Typically, U-234 and U-238 dominate, and thorium isotopes are also soluble. Although not determined in [19], radium isotopes and Pb-210 occur only in minor concentrations.

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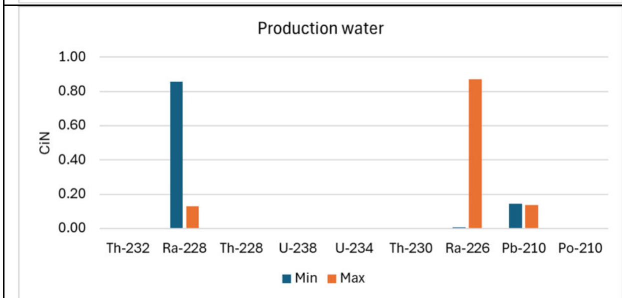

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Produced waters from oil production are high-saline **brines.** Data on concentration ranges given in [84] show that these brines typically contain high radium concen-trations and practically no uranium or thorium isotopes. Pb-210 may occur to a minor degree.

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</table>

3.5.3 Which ores and minerals have enhanced activity concentrations?

Table 3-4 shows the range of radionuclide values found in ores and minerals mentioned in the positive lists of Table 3-1. Values are estimated from data in the cited papers. Because of the high data variability, values are given as ranges that cover the typical order of magnitude. Extreme values outside the ranges shown here are possible. It is important to note that results can vary significantly and it is important to have analyses undertaken.

TABLE 3-5: TYPICAL RANGES OF ACTIVITY CONCENTRATIONS IN ORES OR MINERALS RELEVANT FOR INDUSTRIAL PROCESSES WITH NORM

Valuable Element	Mineral	Th-232sec	U-238sec	Data source
		Bq/g	Bq/g	
REE, Niobium, Tantalum	Monazite	80 – 800	10 – 100	[63]
	Heavy mineral sands	0.3 – 3	0.2 – 2	[63]
Titanium	Ilmenite	0.2 – 2	0.1 – 1	[64]
	Rutile	0.1 – 1	0.1 – 1	[64]
Phosphorus	Sedimentary	0.01 – 0.1	0.4 – 4	[66]
	Igneous[	0.01	0.05 – 0.5	[66]
Zirconium	Zircon, Zirconia	0.3 – 3	1 – 10	[68]
Aluminum	Bauxite	0.03 – 0.3	0.08 – 0.8	[70]
Lead	Galena	0.003 – 0.03	0.001 – 0.06	Authors
Iron	Hematite	0.008 – 0.08	0.006 – 0.06	[85],[86],[87],[74]
Carbon (fuel)	Hard coal		0.003 – 0.03	
	Brown coal, lignite		0.003 – 0.03	
Silicon	Quartz	0.0003 – 0.003	0.001 – 0.01	Authors

The data in Table 3-5 indicate that the activity concentrations of many ores and minerals are well below the exemption value of 1 Bq/g for each radionuclide in the natural decay series. Nevertheless, the "production of copper, zinc, lead, and iron and steel" is listed by the IAEA and ICRP as a NORM sector. This classification is justified because industrial processes may increase activity concentrations in various process streams or waste streams.

3.6 How do beneficiation processes change the radionuclide composition patterns of NORM?

Beneficiation processes in the mining industry are physical processes and, sometimes, limited chemical operations (such as flotation using a frothing agent) used to increase the concentration of valuable minerals. Typical such processes are summarized in Table 3-6.

Only a few specific studies on the radionuclide behavior in beneficiation processes have been published. Some examples of nuclide compositions after beneficiation processes are shown in Figure 3-6.

Because beneficiation typically involves only physical processes, the effects on radioactivity remain limited. Radionuclides may concentrate in products or waste streams, but in general, the radionuclide equilibrium of the ores or minerals is maintained. However, the U/Th Ratio may change during this step.

Some examples of beneficiation are shown in Figure 3-6. The diagrams demonstrate that (within the measuring uncertainties) the radioactive equilibria in the decay chains are not changed. Because the minerals are partially separated, the uranium/thorium ratio may be shifted.

TABLE 3-6: BENEFICIATION PROCESSES

Stage	Processes	Purpose
1. Comminution	Crushing and grinding	To liberate valuable minerals from the gangue (waste rock).
2. Size classification	Screening or hydrocycloning	To separate particles by size for further treatment.
3. Concentration / Separation	Physical or physicochemical methods (like gravity, magnetic, flotation, etc.)	To increase the grade of the desired mineral.
4. Dewatering	Thickening, filtration, drying	To remove excess water from the concentrate and tailings.

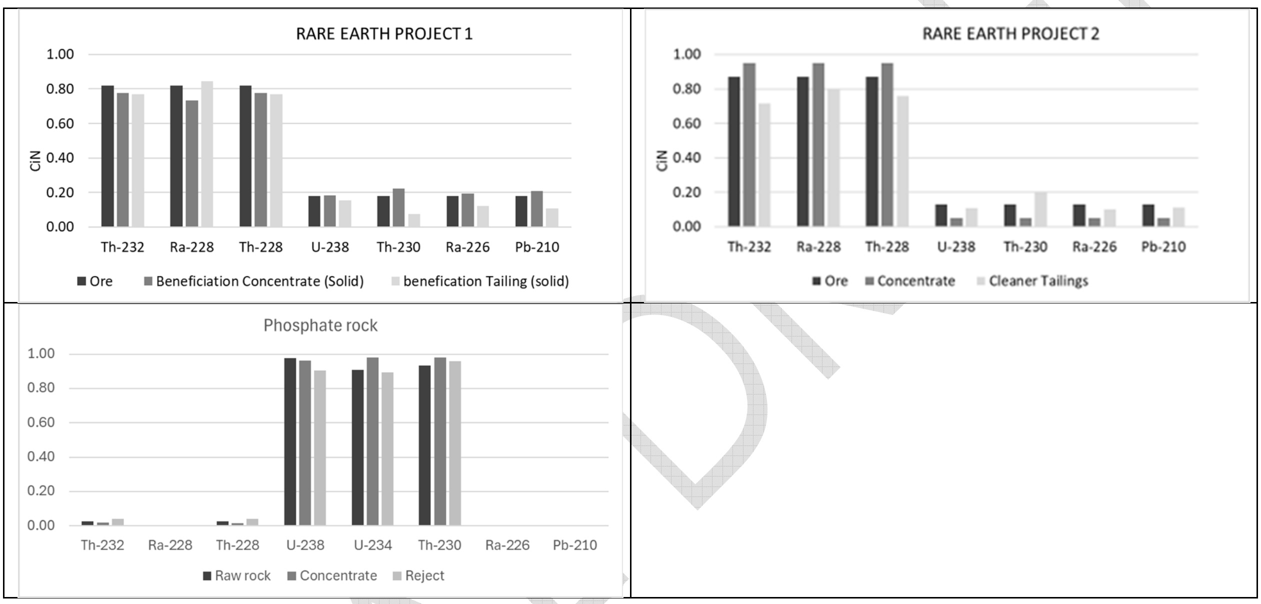


FIGURE 3-6: EFFECTS OF BENEFICIATION, INCLUDING A FLOTATION STEP, ON THE NORMALIZED RADIONUCLIDE COMPOSITION OF DIFFERENT ORES

Data: [88], [89]

3.7 How do chemical processes in aqueous solutions affect NORM?

3.7.1 Introduction

Aqueous (water-based) solutions are widely used to extract metals from ores, concentrates, and recycled materials. Identifying where radionuclides occur and whether they may be accumulating in different parts of the process line is essential for radiation protection.

Once dissolved in industrial streams, radionuclides will remain in the liquid effluent until a solid phase forms, either as a product or as an unwanted precipitate on or within infrastructure elements such as tanks, filters, or pipelines. In general, this precipitation occurs when the stream chemistry is intentionally altered to promote the formation of solids in which the commodity of interest is concentrated, or when the acidic stream is buffered with alkaline reagents. This is the case with fertilizers and other phosphate products, which accumulate NOR like uranium and Pb-210.

More frequently, NOR from industrial effluents end up in solid matrices that are usually disposed of as residues. This is the case of sludge from the titanium pigment industry, which concentrates Ra-226 [66],[67], and the (in)famous phosphogypsum [90], with relatively high activity concentration of Ra-226.

It is important to note that the chemical concentrations of radium, polonium, and actinium in all industrial effluents are too low to form their own mineral precipitates (e.g., $RaSO_4$, $RaCO_3$, PoO_2, …). Therefore, e.g., radium must be co-precipitated in minerals like gypsum, clays, and carbonates. Since the crystal lattices of these minerals are not well suited to accommodating radium, the total activity concentration in these solid residues is frequently low to moderate, ranging from 1 to 20 Bq/g.

In contrast, NORM found as scaling or incrustations can, in some cases, can be very different. The minerals forming these precipitates can easily co-precipitate NOR during formation, leading to very elevated activity concentrations, sometimes higher than 1,000 Bq/g. Two main examples illustrate this type of NORM:

(1) Precipitation of barite ($BaSO_4$) coupled with radium co-precipitation in the offshore oil fields, in the phosphate industry, and in geothermal operations,
(2) precipitation of galena (PbS) with high accumulation of Pb-210.

In the first case, barite forms when sulphate waters mix with Ba-Ra-bearing fluids. Since barium sulphate and radium sulphate form a miscible solid solution, radium can be incorporated into barite in a virtually unlimited amount. Also, barium replacement by radium in pre-existing barite precipitates has been experimentally observed, increasing the activity concentration of Ra isotopes in the precipitates over time. In the case of lead, the existence of stable Pb isotopes is essential. In some geothermal wells, preserved low Eh conditions in which sulfur is found as sulfide, can allow the formation of metal sulfides whose solubility is very low, leading to, for example, PbS that includes Pb-210.

Finally, in some cases, NOR is discharged within the effluent; an example is Ra-226 in the phosphate industry, when hydrochloric digestion is applied.

3.7.2 Leaching (digestion)

In hydrometallurgy, "digestion" (or *leaching*) refers to selectively dissolving valuable metals from ores, concentrates, or residues for later processing for purification and recovery. The main digestion (leaching) methods are compiled in Table 3-7.

TABLE 3-7: MAIN DIGESTION (LEACHING) METHODS IN HYDROMETALLURGY

Method	Main Reagent(s)	Typical Metals
Acid leaching	H_2SO_4, HCl, HNO_3, HF	U, REE, Cu, Ni, Co, Zn; Ti
Alkaline leaching	NaOH, Na_2CO_3	Al, U, Mo, W
Ammonia leaching	NH_3, NH_4 salts	Cu, Ni, Co
Bioleaching	Microbes, Fe^{3+}	Cu, U, Au
Cyanidation	NaCN, O_2	Au, Ag

Data on the radionuclide composition of NORM produced in hydrometallurgical processes are mainly available for sulfuric acid digestion. Other leaching methods are less frequently used, and representative data on NOR from such leaching were not found in the literature.

Sulfuric acid leaching

Examples that show the changes in the composition of the leached minerals and the composition of the leaching agent for sulfuric acid digestion of different types of raw materials are shown in Figure 3-7. For comparison, the composition of the processed ores is also given.

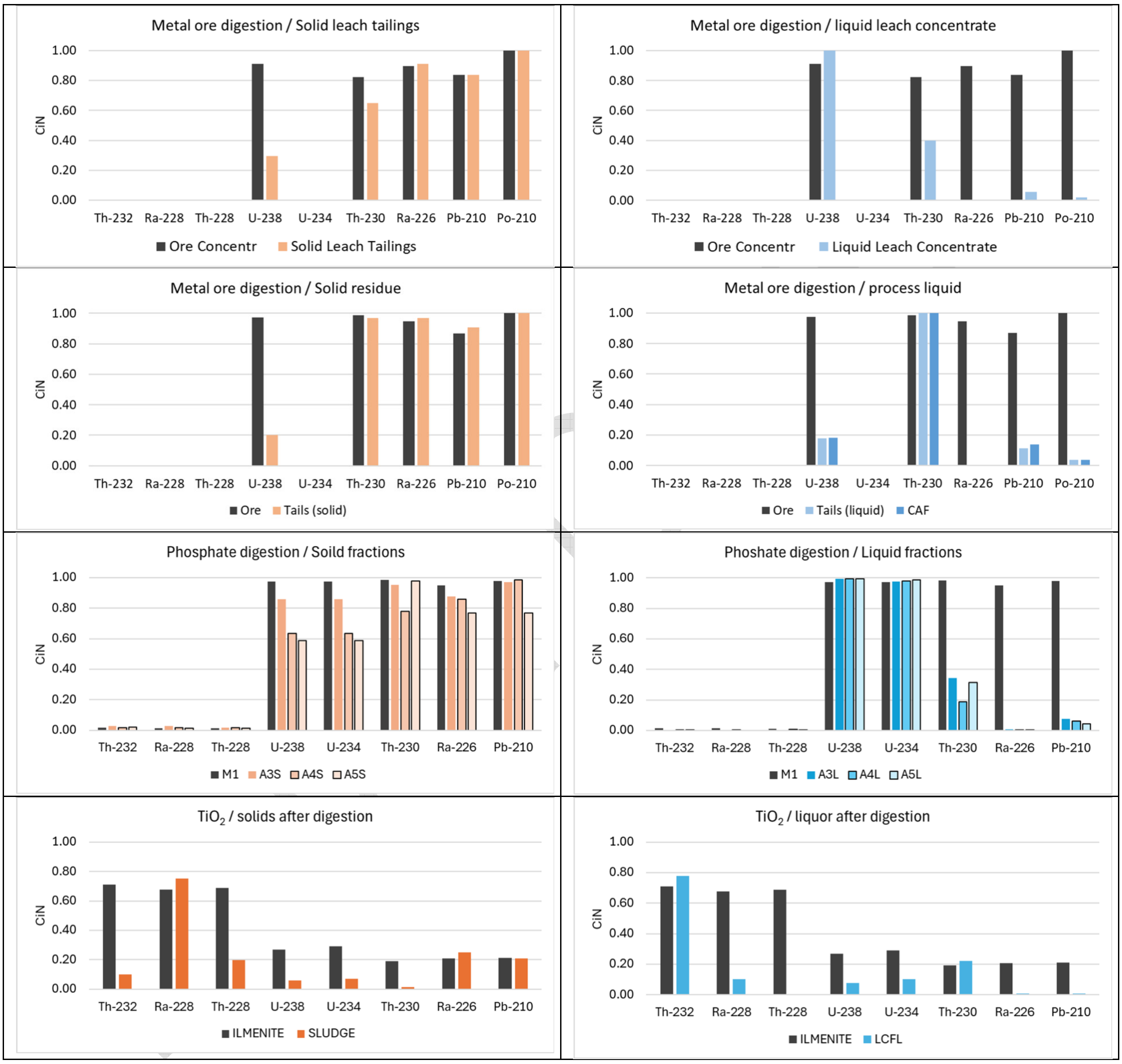


FIGURE 3-7: EFFECTS OF SULFURIC ACID DIGESTION ON THE NORMALIZED RADIONUCLIDE COMPOSITION OF DIFFERENT TYPES OF RAW MATERIALS.

Data: Metal ore digestion from [88], phosphate ore digestion from [67], TiO_2 processing from [65]. Abbreviations have been taken from the literature. Black columns: Ore composition for comparison.

The diagrams show clearly that:

- Sulfuric acid digestion selectively mobilizes uranium and thorium into solution, leaving the majority of the other radionuclides. The concentrations of uranium and thorium in the solid tailings materials are therefore significantly reduced. The efficiency of extraction depends on the minerals and the specific procedural conditions (pressure, temperature, duration of leaching).
- Main parts of the radium isotopes and Pb-210, Po-210 remain undissolved in the solid.
- In sulfuric acid liquor, uranium and thorium isotopes dominate the radionuclide composition. Radium, Pb-210, and Po-210 occur only in minor proportions.

Hydrochloric (HCl) leaching

Hydrochloric leaching is a digestion method that is used to dissolve metal oxides and carbonates because they readily react with HCl. From the industrial sectors with NORM mentioned in Table 3-1, the production of phosphates, titanium dioxide, copper, zinc, and lead may include hydrochloric acid leaching. Hydrochloric leaching is also applied for the bleaching of clay minerals for production of Fuller´s Earth.

Unlike sulfuric acid leaching, hydrochloric acid leaching dissolves nearly all radionuclides [91]. Depending on subsequent processes, these radionuclides may accumulate in precipitates or be discharged by effluents. The behavior of uranium and radium in the hydrochloric acid route for phosphate rock processing is described in [92].

A specific process based on chloride digestion is used for TiO_2 production. In the first step of the chloride process [93], a chemical reaction between titanium ores and carbon and chlorine gas at temperatures of about 1000°C under reducing conditions leads to the formation of gaseous $TiCl_4$. This reaction product is then refined using a rectification procedure before going through an oxidation stage. The following behavior of NOR in this process was assessed by McNulty [93]:

- U – will chlorinate and pass forward in the gas stream.
- Th – the vast majority will pass forward (Boiling point 940°C).
- Ra – $RaCl_2$ only melts at 1000°C so there is the possibility of some retention within the chlorinator.
- Pb – vast majority will pass forward (b.pt 950°C)
- Bi - will chlorinate and pass forward in the gas stream.
- Rn – will remain in gas phase

Alkaline leaching

Alkaline leaching is part of the Bayer process for producing alumina from bauxite. After bauxite ore is crushed, washed, and dried to remove impurities, it is mixed with a sodium hydroxide (caustic soda) solution. At temperatures of 150-200°C, aluminum compounds are dissolved from the ore. The remaining residue is known as “red mud”.

Normalized radionuclide compositions of red mud are shown in Figure 3-8. Considering measurement uncertainties, the German data show secular equilibrium in each decay series, with a slight depletion of Pb-210. Other data evaluated in Figure 3-8 indicate some Ra-226 depletion. The effect is not very pronounced.

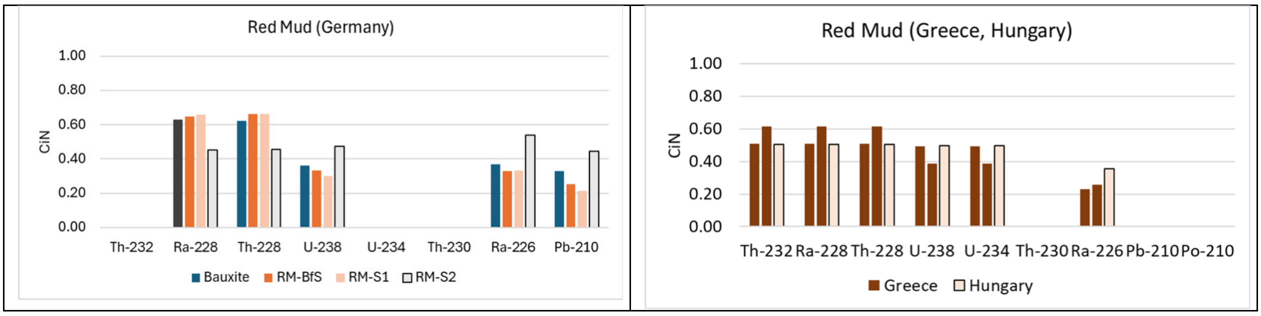


FIGURE 3-8: NORMALIZED RADIONUCLIDE COMPOSITION OF RED MUD (BAUXITE LEACHING).

Left: Data from Germany [69]; Greece [94], Hungary [95]

Caustic soda leaching is also a step in REE processing. Data given in [63] show that only Pb-210 is dissolved in this alkaline leaching. The percentage of dissolved lead is given as 15 %. Uranium, thorium, and radium remain in the solid phase.

Note that leaching will result in acidic or alkaline tailings and waste streams that may require further consideration before disposal.

3.7.3 Precipitation processes

What types of processes are relevant for NORM?

Leaching processes are used to selectively extract valuable materials (metals) from ores or intermediate materials into a form that enables further refinement. Converting the dissolved form back into a solid is a necessary additional step in the process chains. Precipitation steps usually do this.

A widespread method is the precipitation of sulfates with lime. This is particularly essential in phosphate processing. The chemical reaction of the sulfate digestion of phosphate ores is

$Ca_3(PO_4)_2 + 3H_2SO_4 \rightarrow 3CaSO_4 + 2H_3PO_4$

and produces large amounts of phosphogypsum ($CaSO_4$). Because radium and calcium are earth alkali elements, radium is co-precipitated with the gypsum.

Precipitation with lime is also used in wastewater treatment and to neutralize highly acidic water from mines and precipitate dissolved metals. Due to the large amounts of lime generated in such processes, Ra-226 (Ra-228) activity concentrations are usually in a low or median range (cf. Section 3.10).

Another precipitation process that plays a significant role in generating NORM is the precipitation of $Ba(Sr)SO_4$ and, to a lesser extent, $Ba(Sr)CO_3$ from brines. Anaerobic brines in which sulfates are reduced to sulfide are typical water types in many oil and gas reservoirs. These brines contain naturally enhanced concentrations of radium isotopes (Ra-226, Ra-228, Ra-224). When brine is extracted along with the oil or gas (produced water), sulfides are converted to sulfates, and insoluble Ba and Sr salts are formed. These salts precipitate and form hard scales on the inside of the installation, or accumulate as sludge in tanks or other components of the production facilities. As the earth alkali element Ra is chemically similar to Ba and Sr, Ra is incorporated in $Ba(Sr)SO_4$ and $Ba(Sr)CO_3$ scales and sludges.

Because $BaSO_4$ is highly insoluble in hydrochloric acid, precipitation and formation of solid scales with particularly high activity concentrations occur in chemical facilities. Some examples are TiO_2 production by the hydrochloride process, dicalcium phosphate production [96], [98], and Fuller's Earth.

Sulfuric acid processing (Phosphate ore processing)

Radionuclide compositions of different solid phases of pulp or sludge from a phosphate processing plant, as well as phosphogypsum, are shown in Figure 3-9.

The diagrams demonstrate that the dominant radionuclides in phosphogypsum are Ra-226, Pb-210, and Po-210, with uranium activity concentrations significantly lower. This is because uranium is soluble in phosphoric acid and remains in the liquor (see Figure 3-9, mean row right; lower row left).

Th-230 in phosphogypsum shows a relevant activity percentage. While data given in [66] indicate that the Th-230 activity is only half of Ra-226, the results given in Bolivar et al. [67] indicate that Th-230 reaches the highest activity concentrations in phosphogypsum. This must be considered when estimating inhalation doses (see Section 5.6.5) or classifying phospho-gypsum regarding its status according to the hazardous goods regulations (see Section 8.4.1).

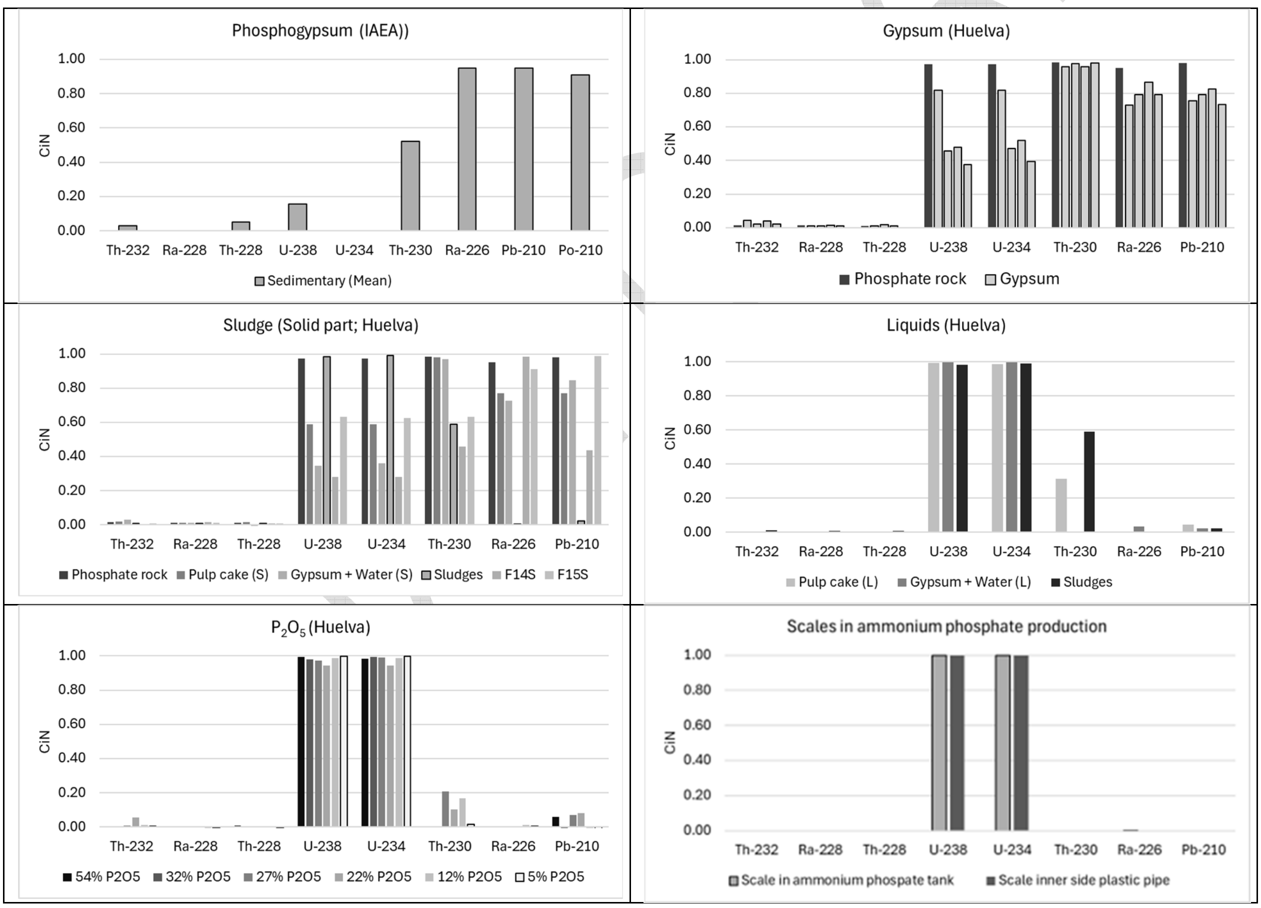


FIGURE 3-9: ***NORMALIZED RADIONUCLIDE COMPOSITION OF DIFFERENT MATERIALS FROM PHOSPHATE ORE PROCESSING, SULFURIC ACID PROCESS***

Upper row left: Database IAEA Table 56 in [66]. Data selection: Only data sets with more than 2 different radionuclides. Mean from 9 data sets. Upper row right: Data Huelva from [67]. Phosphate rock for comparison. Middle row left: Intermediate process materials. Data from [67]. Lower row left: Phosphoric acid products. Data from [67]. Lower row right: Scales from a phosphate further processing. Data from [96].

Sulfuric acid processing (TiO_2 sulfate process)

Because Ilmenite and other TiO2 ores contain significant amounts of iron, the iron must be removed from the process. This is done by the removal of the iron sulfates (Copperas, Monohydrate). Analytical results published by Matero [65] demonstrate that radium (Ra-228) is transferred into the iron sulfates, while thorium seems to be transferred into the precipitation product Red Gypsum (see Figure 3-10).

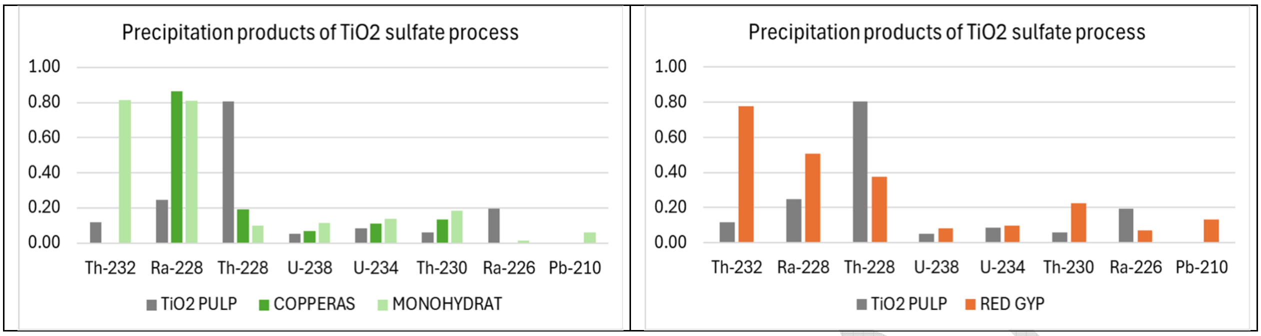


FIGURE 3-10: EFFECTS OF PRECIPITATION STEPS IN THE SULFATE PROCESS OF TIO2-PRODUCTION.

Data from [65]. Grey columns (left): TiO_2 pulp composition for comparison.

Ammonium phosphate production

One possible further processing of phosphoric acid (H_2PO_4) is the production of ammonium phosphate. Ammonium phosphate is primarily used as a high-nutrient, nitrogen-phosphorus (NPK) fertilizer. Beyond agriculture, it is used as a fire retardant in extinguishers and building materials, a yeast nutrient in baking/winemaking, and for several other purposes. The chemical reaction is

$$H_3PO_4 + NH_3 \rightarrow NH_4\,H_2PO_4$$

Because phosphoric acid from sedimentary ores contains dissolved uranium, the uranium reacts and may form less soluble compounds, such as ammonium uranyl phosphate or ammonium diuranate (ADU). In a Belgian phosphate plant, scale with a uranium-dominated nuclide composition was detected in an ammonium phosphate tank and in the inner side of a plastic pipe [96]. From the data given in [96] the normalized nuclide composition in Figure 3-9 is derived.

Dicalcium Phosphate (DCP) production

Dicalcium Phosphate (DCP) is an animal feed. It can be produced by reacting phosphoric acid, usually obtained from a sulfuric acid process, with lime. Another way is by treating the phosphate rock with hydrochloric acid, leading to crystalline dicalcium phosphate by the reaction [97]

$$Ca_{10}(PO_4)6F_2 + 18HCl \rightarrow 9CaCl_2 + CaF_2 + 6H_3PO_4H_3PO_4 + CaCO_3 \rightarrow CaHPO_4 + CO_2 + H_2O$$

These complex reactions, with a first step in a strong acidic milieu, produce CaF_2-sludge as a waste and several incrustations in the wet-process areas as scales, crusts, and sediments [98].

Normalized nuclide compositions based on data given by Pepin [96] from a Belgian DCP plant and Grandia [98] from a Spanish DCP plant are shown in Figure 3-11. In both studies the radionuclides of the Th-232-series were not considered because their activities are negligible from a radiation protection point of view. The diagram shows that CaF_2 carries both uranium and radium. In the Belgian plant, two different types of scales were detected. One type represents scales with a dominant uranium activity, and the second type scales with a dominant radium. In the Spanish plant, the authors in [98] state:

- Radium activity concentration is the main concern since it is very mobile in the effluents and can accumulate in radiobarite, which is the most effective sink.
- Unlike phosphoric acid-producing plants using the H_2SO_4 route, NORM in plants using HCl is found in very insoluble mineral matrices.
- Pb-210 and Po-210 are not directly deposited, and their activity results from the radioactive ingrowth.

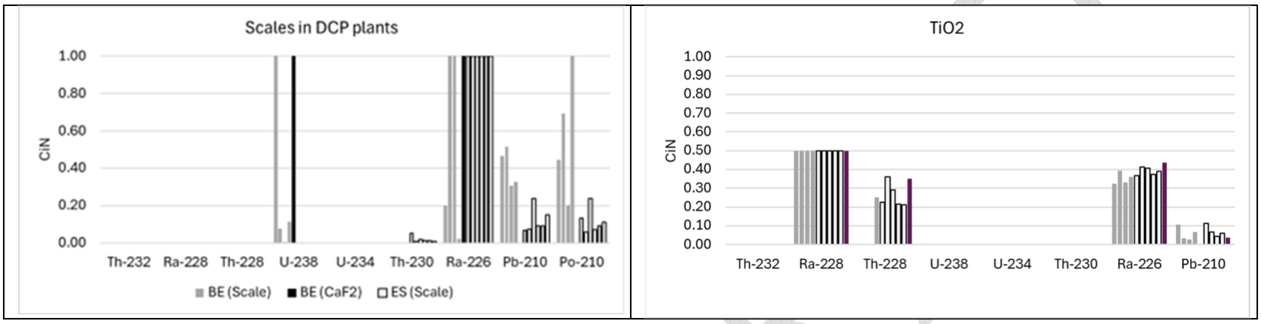


FIGURE 3-11: NORMALIZED ACTIVITY CONCENTRATIONS OF SOLID PRECIPITATION RESIDUES.

Left: from a DCP-process in a Belgian plant (BE) [96] and a Spanish plant (ES) [98]. Right: Radium-bearing residues of a TiO_2-production [Authors].

Scales and sludges in oil or gas production

Figure 3-12 shows radionuclide composition of produced water, hard scales, and sludges from oil and gas production.

Scales are Ba(Sr) sulfates and carbonates, which are precipitated from produced water. Because produced water does not (or only in negligible amounts) contain U-238 (with U-234), Th-232, and Th-230, these Ba(Sr)-scales contain only radium isotopes (Ra-226, Ra-228) and their daughters. Th-228 grows in due to the decay of Ra-228. Therefore, its activity concentration depends on the age of the scale or sludge. Examples of such scales are shown in Figure 3-12 (Diagrams top; IOGP: "hard scale"; Germany: Samples Ba).

Although Pb-210 is also present in Ba(Sr) scale and sludges due to the in-growth from Ra-226, scales and sludges there are also sulfide-rich scales and sludges (FeS, PbS, ZnS) with predominantly Pb-210 activity. Such sludges form when produced water contains H_2S and Pb^{2+}, leading to precipitation as PbS (galena). Mixed Fe–Pb–Zn sulfide sediments are commonly referred to as "Black Powder" and can trap Pb-210 in high concentrations. Examples of sludges with predominantly Pb-210 activity are shown in Figure 3-12 (IOGP: "Max (Sludge)" and Germany: Bo and Vo).

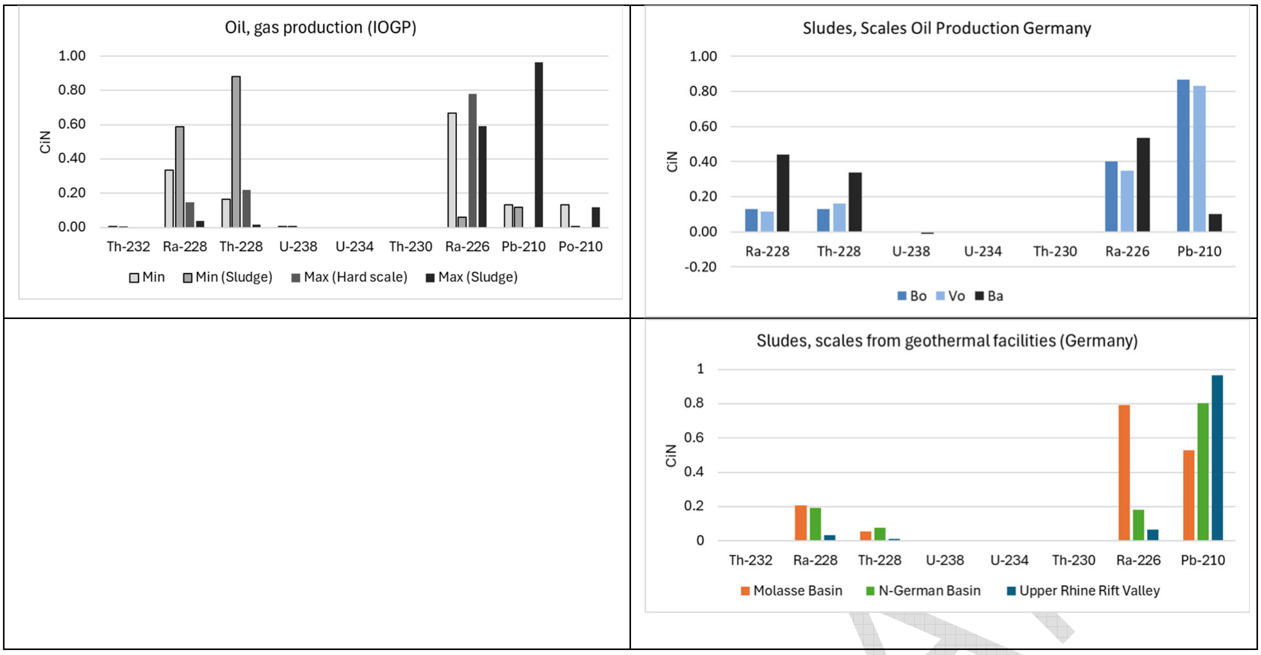


FIGURE 3-12: NORMALIZED RADIONUCLIDE COMPOSITION OF SLUDGES AND SCALES FROM OIL AND GAS PRODUCTION, AND GEOTHERMAL FACILITIES

Scales and sludges in geothermal facilities

For geothermal energy production, volcanic areas are not the only source; deep heat reservoirs are also utilized. These deep heat reservoirs frequently contain hot brines with a similar composition to the brines in the oil or gas reservoirs. Based on the median values given in the German study [99], the radionuclide compositions of scales and sludges of three different reservoirs are shown in Figure 3-12 (Bottom, right). While the Bavarian Molasse Basin contains weakly mineralized water, the reservoirs in the Upper Rhine Rift Valley and the North-German Basin contain highly mineralized brines. In scales and sludges of these latter two reservoirs, Pb-210 is the dominant radionuclide.

Similar radium-dominated sediments are known from hard coal mining in Poland [100] and Germany [101]. The reason is that in the deep underground in Central Europe Zechstein salt deposits can lead to the formation of brines. Coal deposits without such salinization of deep groundwater may therefore exhibit different compositions of discharges and their sediments.

3.7.4 Sorption processes

Sorption is the process where one substance in a gas or liquid attaches to a solid substance. It plays a significant role in drinking water treatment.

Radionuclides and chemical trace substances are removed by adsorption, i.e. fine particles and dissolved materials adhere to sand surfaces. An important part of the process uses iron oxides (Fe_2O_3, Fe_3O_4) and iron hydroxides ($Fe(OH)_3$, $FeOOH$). They form naturally on the surface of sand grains or are deliberately added as coatings. Iron oxides/hydroxides have a high surface area and many reactive sites (–OH groups) that can bind negatively charged species through chemical attraction.

Normalized radionuclide compositions of water treatment residues based on data from Germany and Czechia are shown in Figure 3-13. The dominant activity is from radium isotopes. Compared to water, the Ra-shares are higher, which indicates a high sorption efficiency. Unlike the scales in oil production, uranium is also found in drinking water treatment residues. The Czechian data [36] show that the U-234 activity in the residues is also higher than that of U-238 and corresponds to the activity ratio U-234 / U-238 in the treated water. Th-228 is not produced by sorption but by regrowth from Ra-228.

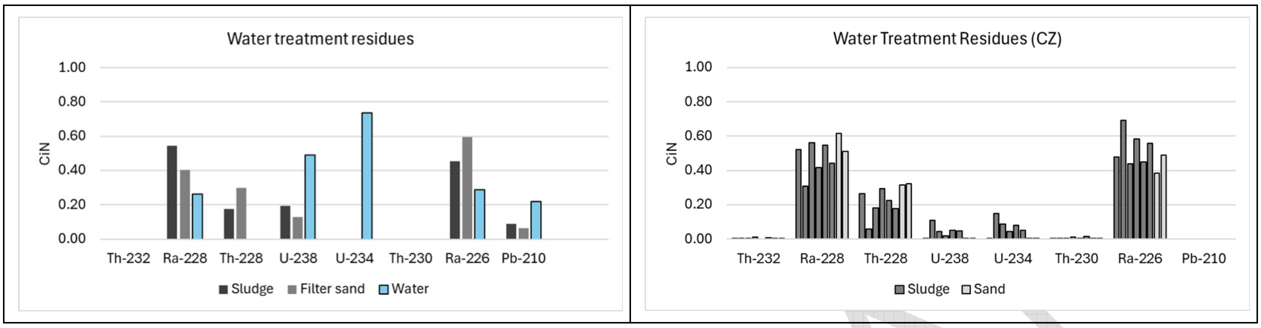


FIGURE 3-13: NORMALIZED RADIONUCLIDE COMPOSITION OF DRINKING WATER TREATMENT RESIDUES

Germany (left) [102] and Czechia (right) [103]. Data "water" for comparison from [80]

A very specific drinking water treatment is the extraction of uranium with ion exchange resins. This step is applied if the natural uranium concentrations exceed the national limits for drinking water. The loaded ion exchangers contain only uranium and exhibit significant radioactivity.

3.7.5 Example: Complex mining and processing line

The conceptual changes in radionuclide compositions in a multi-step hydrometallurgical process are shown in Figure 3-14. The diagrams are based on measurements focused on radionuclides from the U-238 decay series. To make it clear that radionuclides of the Th-232 series also occur and behave according to their chemical properties, a fictive "reference ore" was considered in the diagrams for comparison.

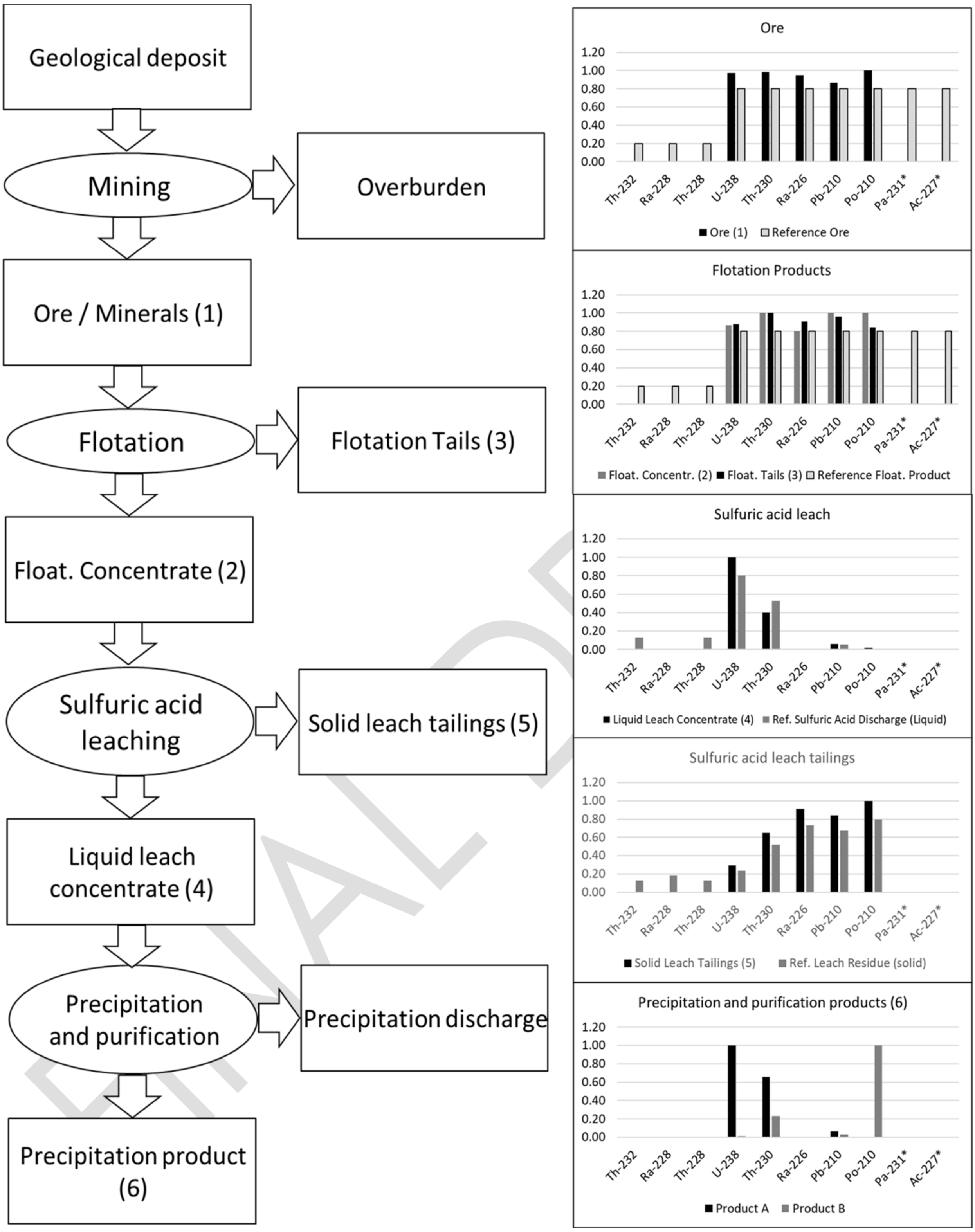


FIGURE 3-14: NORMALIZED RADIONUCLIDE COMPOSITIONS IN A MULTI-STEP HYDROMETALLURGICAL PROCESS

3.8 How natural gas forms NORM

A specific kind of precipitation is the deposition of Pb-210 from natural gas.

Natural gas is extracted from sedimentary rock reservoirs (sandstone, conglomerate, shale, and, in some cases, claystone). These rocks possess natural radioactivity due to radionuclides from the decay series of U-238, U-235, and Th-232, as well as K-40. Besides the radioactivity in the produced water (as discussed in the previous section), the radioactivity of natural gas is determined by the noble gas radon, which is produced from Ra-226 through radioactive decay, and its isotope Rn-222 (see Figure 2-13). Due to its short half-life, Thoron (Rn-220 from the Th-232 decay chain) does not play a significant role in natural gas streams.

A histogram of Rn-222 in natural gas is shown in Figure 3-15. This diagram is based on about 1200 measurement data from the Netherlands. The samples were taken at wellheads or at the transport lines. In some cases, samples were taken from wells that weren't producing (no gas flow). If a well hasn't been producing for a few weeks, the radon concentration can be as low as 0 Bq/m³.

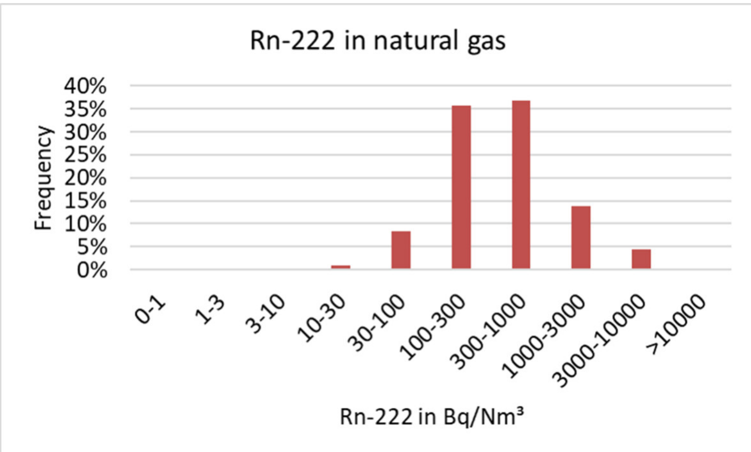


FIGURE 3-15: HISTOGRAM BASED ON ABOUT 1200 MEASURING DATA, COURTESY OF NAM B.V., THE NETHERLANDS

According to Figure 3-15 the most frequent Rn-222 concentrations fall in the range between 100 Bq/Nm³ and 1000 Bq/Nm³. When interpreting the data, it must be considered that the measuring results are given in "Bq/Nm³", which means they refer to a pressure of 1 bar. The wellhead pressure of new natural gas fields in the Netherlands is usually above 100 bar and can be as high as 600 bar (the pressure in the formation at ~3000 meter depth will be higher). When production starts, the pressure goes down. If fields are reaching end-of-life, the pressures at producing wellheads are in the range of a few bars up to ~120 bar. The Rn-222 concentration in natural gas pipelines in which gas is transferred at 100 bar is 100-fold higher than at normal pressure, reaching 100,000 Bq/m³ or even higher. The estimations in Box 3-1 show that this level does not require enhanced radioactivity in the host rock of the reservoirs. It can therefore be assumed that the extracted natural gas has an Rn-222 concentration (at reservoir pressure) of approximately 100,000 Bq/m³.

Due to its noble gas character, radon remains in the gas phase and is practically not retained by purification systems. However, due to its relatively short half-life of 3.86 days, Rn-222 decays relatively quickly.

> **BOX 3-1: ESTIMATIONS ON RN-222 CONCENTRATIONS IN NATURAL GAS RESERVOIRS**
>
> With an average uranium content of 3.2 ppm, the activity concentration of Ra-226 in the rock is approximately. 40 Bq/kg and, at a rock density of approx. 2 Mg/m³, the volume-related Ra-226 concentration is 80,000 Bq/m³. Radioactive decay constantly produces Rn-222 from Ra-226, with the activity per unit volume corresponding to that of Ra-226. Because of its noble-gas character and the recoil energy from radioactive decay, part of the radon formed in the rock enters the pore spaces. This release of radon from a solid (mineral) into adjacent air or water is referred to as emanation ('flowing out'). The characteristic parameter is the emanation factor E_{Rn}, which describes the proportion of Rn-222 activity in the pore space relative to the Rn-222 activity in the rock (see Chapter 2) and can range from less than 5% to more than 40%. If we assume a value of E_{Rn} of 20% and a pore fraction of 20% for a rough estimate, the concentration of Rn-222 in a (regular) natural gas reservoir is 80,000 Bq/m³.

In pipelines, natural gas is transported at about 100 bar and velocities of 5 m/s (432 km/day). Therefore, in sections of a gas pipeline far away from the geological reservoir, a significant Rn-222 concentration may occur.

Suppose a continuous Rn-222 concentration of 10,000 Bq/m³ in a 1 km section of a pipeline with an inner diameter of 1 m (Volume 785 m³). In this section, 7,850 Bq of Rn-222 are constantly present, and its decay produces Pb-210.

Despite this low rate of radiogenic Pb-210 production, a significant activity accumulates over time (see Figure 2-14). However, Pb-210, as an isotope of the chemical element lead, is not a gas but behaves like a metal. Its predecessors, Po-218, Pb-214, Bi-214, and Po-214 (see Figure 2-13), which are also metallic, quickly attach themselves to particles. The deposition of particles, possibly also due in part to direct interaction of the atoms with the metal surface of the pipe, leads to the formation of depositions with increased Pb-210 activity.

As a result of these processes, the inner surface of natural gas pipelines and installations may become covered with a thin layer of Pb-210 (lead film) or particulate matter (black powder). Because the activity of Po-210 is produced by a slowly increasing activity of Pb-210, Po-210 remains much longer in a deficit compared with Pb-210 than expected from its half-life (see Figure 3-16, right).

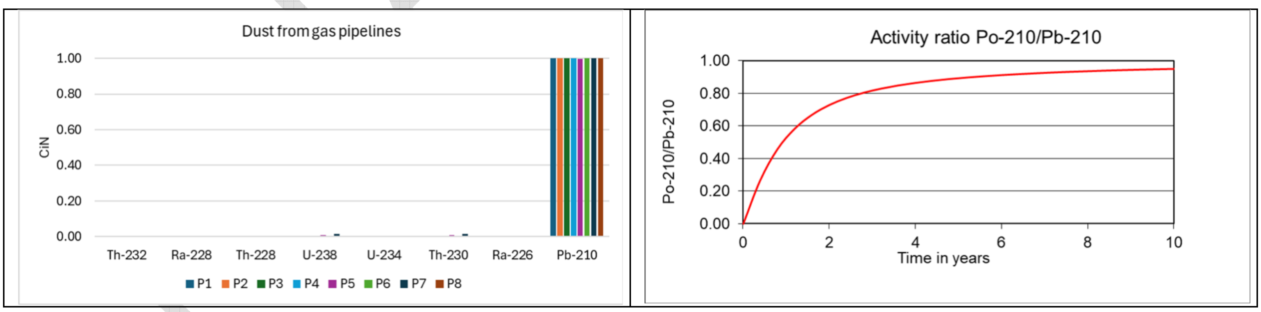


FIGURE 3-16: LEFT: NORMALIZED RADIONUCLIDE COMPOSITION OF PIGGING RESIDUES OF A NATURAL GAS PIPELINE

Data: Authors. Right: temporal change of the activity ratio Po-210/Pb-210

Rn-222 is also still present in natural gas when compressed to liquified natural gas (LNG). Therefore, LNG tankers contain a considerable amount of Rn-222 when loaded. As the LNG tanker voyage usually takes a few weeks, almost all Rn-222 is decayed to Pb-210 at the port of arrival. Small volumes of Pb-210 containing black powder have been demonstrated in LNG carrier tanks and terminals.

As a result of these processes, the inner surface of natural gas pipelines is covered with a thin layer of Pb-210. Because the activity of Po-210 is produced by a slowly increasing activity of Pb-210, Po-210 remains much longer in a deficit compared with Pb-210 than expected from its half-life (see Figure 3-16, right).

Another potential accumulation point for NORM is filter units in pipelines [39].

3.9 How high-temperature processes change the radionuclide composition patterns of NORM

3.9.1 Pyrometallurgical processes

In Table 3-1 the productions of tin, copper, aluminum, zinc, lead, iron/ steel, niobium/tantalum, bismuth, etc., are listed as NORM sectors. Pyrometallurgical processes at high temperatures may produce all these metals. An overview of temperatures in such processes is given in Table 3-8.

The high temperatures are required to provide sufficient energy to break chemical bonds. Two typical types of ores are oxides that must be reduced and sulfides that must be oxidized for the separation of the metal phase. The chemical reaction for production of iron metal from iron oxide (hematite) (iron oxide) is

$2\,Fe_2O_3 + 3\,C + \text{energy} \rightarrow 2\,Fe\ (\text{metal}) + 3\,CO_2$

An example of processing sulfite ores is the manufacture of copper metal from copper sulfides

$CuS + O_2 + \text{energy} \rightarrow Cu\ (\text{metal}) + SO_2$

Because of the required energy, the process temperatures are partly significantly higher than the melting point.

All smelting processes generate **slag**, a mixture of residual chemical elements and flue gases. The flue gases contain, besides the process gases CO_2 or SO_2, vaporized chemical elements. One effect that results in radiologically relevant activity concentrations is the vaporization of Po-210 and Pb-210, followed by adsorption on **dust** particles. Because Po-210 is the decay series radionuclide with the lowest evaporation temperature of 962°C, processes with **temperatures exceeding 900°C** are considered as high-temperature processes in this handbook.

Three other processes closely related to pyrometallurgy are roasting, sintering, and baking carbon electrodes for electric-furnace smelting.

Roasting of ores is a key step in metallurgy, where ore minerals are heated in the presence of oxygen or other gases to bring about chemical changes, such as removing sulfur or oxidizing metals. Typical roasting temperatures range from 500°C to 1,000°C.

Sintering is a process of compacting and forming solid masses of material by heat without melting it. Sintering covers a wide range of techniques and applications. In pig-iron smelting, sintering is a pre-treatment step that produces compacted clinker from mixtures of ore, coke, and lime at temperatures ranging from 900°C to 1300°C.

Baking is a process for preparing graphite or carbon electrodes used in electric furnaces. It carbonizes and strengthens the electrodes by driving off volatile materials and binding the carbon structure. The raw, shaped electrodes (usually made from a mix of coke, coal tar pitch, and other materials) are baked in large ovens at temperatures ranging from 1,000°C to about 1,300°C.

TABLE 3-8: TEMPERATURES IN PRIMARY METAL PRODUCTION FROM ORES (PYROMETALLURGY, ELECTROMETALLURGY). DATA FROM DIFFERENT SOURCES.

Metal	**Melting Point (°C)**	**Typical process temperature (°C)**	**Ore type and processes**
Iron (Fe)	1538	1500–2300	Oxide (hematite). Blast furnace reduction
Copper (Cu)	1085	1150–1350	Sulfide (chalcopyrite). Flash smelting, matte smelting, converting
Lead (Pb)	327	1000–1300	Sulfide (galea) Blast/rotary furnace smelting
Zinc (Zn)	419	1000–1400	Sulfide (sphalerite). Imperial Smelting Furnace, Waelz kiln
Nickel (Ni)	1455	1250–1600	Sulfide. Flash/Matte smelting, Oxide (laterites) Electric furnace
Tin (Sn)	232	1200–1400	Oxide (cassiterite). Reduction smelting
Magnesium (Mg)	650	1200–1400	Carbonate (dolomite). Pidgeon process reduction (thermal)
Chromium (Cr)	1907	1600–1800	Oxide (chromite, associated with iron) Ferrochrome in submerged arc furnace
Manganese (Mn)	1246	1400–1700	Oxide (pyrolusite). FeMn/SiMn ferroalloy smelting
Silicon (Si)	1414	1800–2000	Oxide (quartz). Electric arc furnace, carbothermic reduction of quartz
Titanium (Ti)	1668	800–900	Oxide (rutile, ilmenite). Kroll process reduction (not true smelting)
Gold (Au)	1064	1100–1300	Native metal dispersed in rock. Gold smelting/refining
Silver (Ag)	962	1100–1300	Associated element in Cu, Ni, Pb ores. Produced as a by-product
Aluminum (Al)	660	950	Oxide (bauxite). Hall–Héroult Process (electrolytic reduction)

TABLE 3-9: TEMPERATURES IN THE PRE-TREATMENT PROCESSES OF PRIMARY METAL PRODUCTION FROM ORES

Process	**Typical Temperature range**
Pig iron production and steelmaking	
Sintering	900°C – 1300°C
Non-ferrous metal smelting	1100°C – 1700°C
Roasting of non-ferrous ore (general range)	500°C – 1000°C
Zinc ore roasting	900°C – 1,000°C
Baking (or curing) of electrodes for electric furnaces	1000°C – 1300°C

Normalized radionuclide compositions of slags and dust from some metal smelting processes are compiled in Figure 3-17 and Figure 3-18.

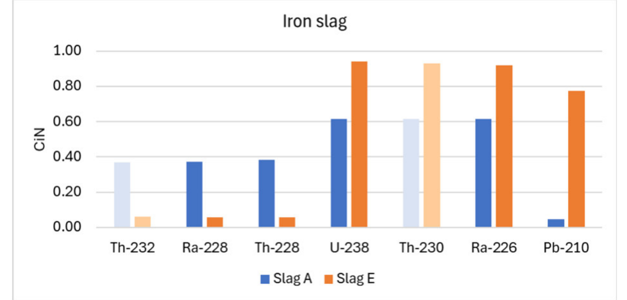


FIGURE 3-17: NORMALIZED RADIONUCLIDE COMPOSITIONS OF SLAGS FROM PYROMETALLURGICAL PROCESSES.

Database [104], [Authors]. Columns on pale colors are supplemented based on equilibrium assumptions.

Iron slag: the available data agree with the knowledge on iron ores, a somewhat higher activity concentration of U-238 compared to Th-232 (see Table 3-3; Table 3-5). The radionuclides of each decay series are in activity equilibrium, except for Pb-210. Pb-210 is (in one case, very significantly) reduced.

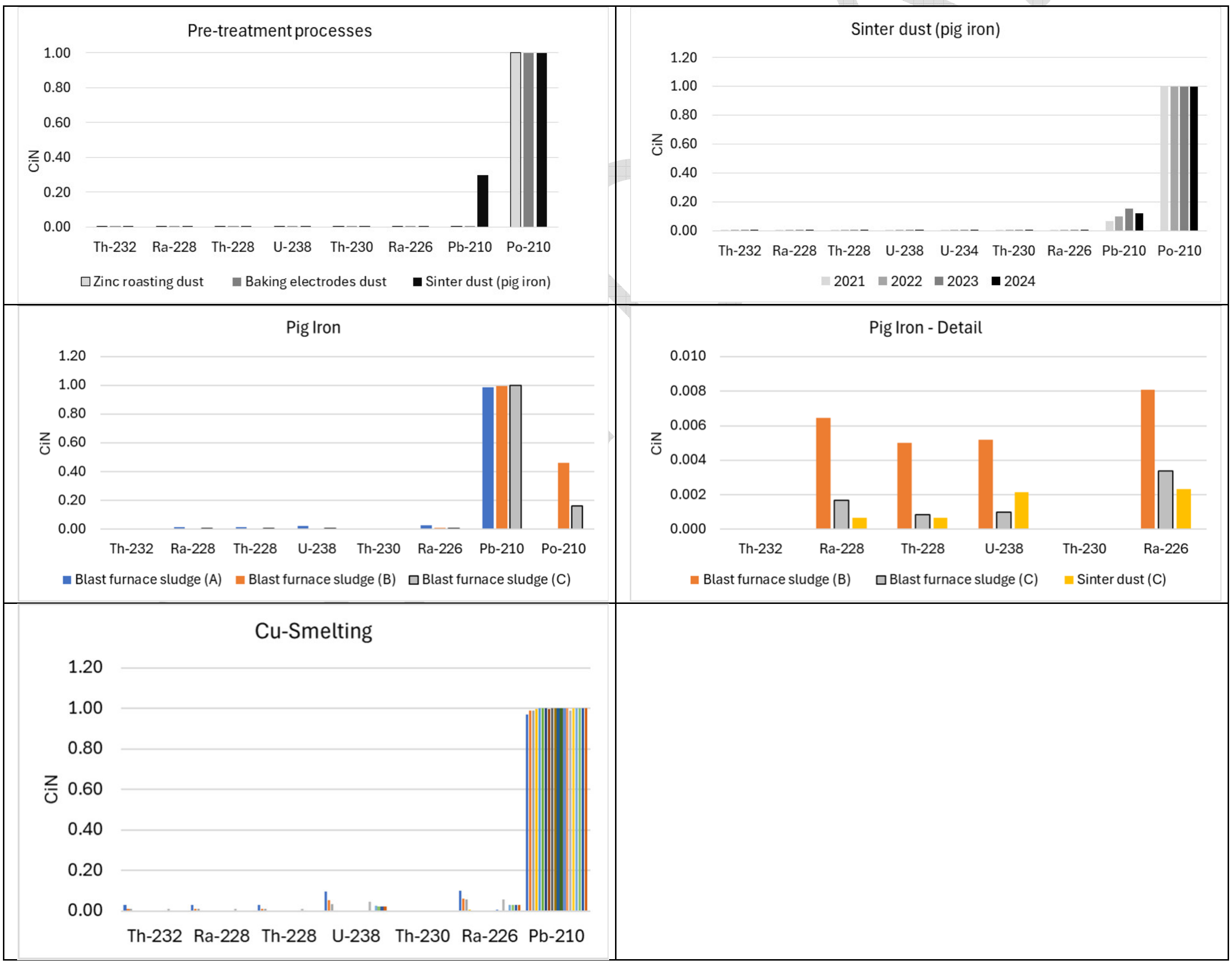


FIGURE 3-18: NORMALIZED RADIONUCLIDE COMPOSITIONS OF DUST FROM PYROMETALLURGICAL PROCESSES.

Data [Authors]. Cu-smelting ("Theisenschlamm") from [69]

In dust from pre-treatment processes like roasting and electrode baking with temperatures between 900 and 1000°C only Po-210 occurs. At zinc roasting zinc sulfide (ZnS, sphalerite) in presence of oxygen reacts at about 950°C to zinc oxide. In the dust of this process only Po-210 occurs in significant amounts. Similar observation have been made in dust from the baking of carbon electrodes. Such dust will not result in enhanced dose rates and will not be noticed by gamma-spectrometry. For pre-checking dust from these processes, an alpha-mode contamination monitor may be used. However, only alpha-spectrometry will yield a reliable result.

Sintering of iron ores (together with other feed materials) is typically maintained at about 1,200°C. This results in dust that is dominated by Po-210 but contains a significant amount of Pb-210. Measurement of Pb-210 by advanced gamma-spectrometry is not sufficient for a radiological characterization.

Pb-210 dominates dust from blast furnace processes. If wet purification of the flue gas stream is applied, the dust is collected as sludge. As a result of the preceding sintering process, the activity of Po-210 is frequently lower than that of Pb-210. The "Detail" diagram in Figure 3-18 shows that the radium isotopes Ra-226 and Ra-228 are slightly enriched compared to their parent nuclides U-238 and Th-232. Considering the smelting and evaporation temperatures in Figure 2-6, this effect is plausible.

Sludges from the flue gas purification of a copper smelter in Germany ("Theisenschlamm") are also clearly dominated by Pb-210. Because this sludge was analyzed several years after its production, Po-210 must be in equilibrium with Pb-210.

3.9.2 Other high-temperature processes

In addition to metal melting, high temperatures are used in many other industrial processes. Table 3-1 lists a selection of such processes involving temperatures above 1000°C. Many of these processes involve materials that do not normally exhibit radioactivity relevant to radiation protection (e.g., glass manufacturing, cement production). For these processes, the use of refractory materials — particularly those containing zirconia — is significant from a radiation protection perspective. However, dust particles from these processes may be enriched in radioactivity and consideration if they are discarded as waste.

TABLE 3-10: TEMPERATURES IN NON-METALLURGICAL PROCESSES

Process	Typical Temperature range
Glass manufacturing	1400°C – 1600°C
Zirconia fusing (sintering)	1450°C – 1600°C
Fused zirconia production	2600°C
Si/FeSi-Production (by- product: Microsilica; Silica fume)	1800°C – 2000°C
Cement production	1400°C – 1500°C
Manufacturing ceramics, abrasives, and refractories	900°C - >2000°C
Incineration and waste treatment	>1000°C
Combustion of coal, oil, or natural gas	1200°C - 1500°C

The processing of zircon sands, the manufacture of ceramics, abrasives, and refractories and coal combustion all involve materials that may be categorized as NORM. Published data of the radionuclide composition of the produced products focus on U-238, Ra-226 and Th-232 (Ra-228, Th-228) as well as K-40. Data on simultaneous determinations of Pb-210 are seldom.

From data of the authors the diagrams in Figure 3-19 are derived. They demonstrate that with the exception of Pb-210 a radioactive equilibrium occurs. Due the vaporization the activity concentration of Pb-210 is significantly reduced.

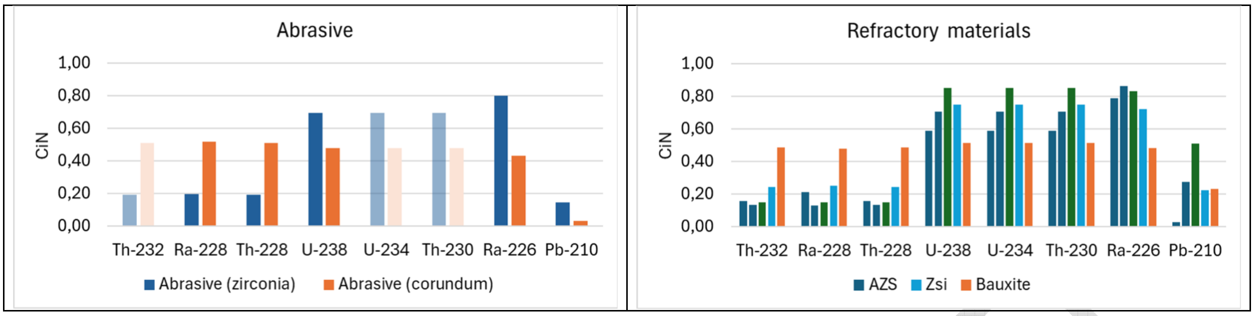


FIGURE 3-19: NORMALIZED RADIONUCLIDE COMPOSITIONS OF PRODUCTS (ABRASIVES AND REFRACTORIES) TREATED AT HIGH TEMPERATURES

Like pyrometallurgical dust, dust from non-metallurgical processes is characterized by higher activity concentrations of Pb-210 and Po-210 than their long-lived precursors in the U-238 series. The diagrams in Figure 3-20 made with data from different industrial sectors clearly demonstrate this.

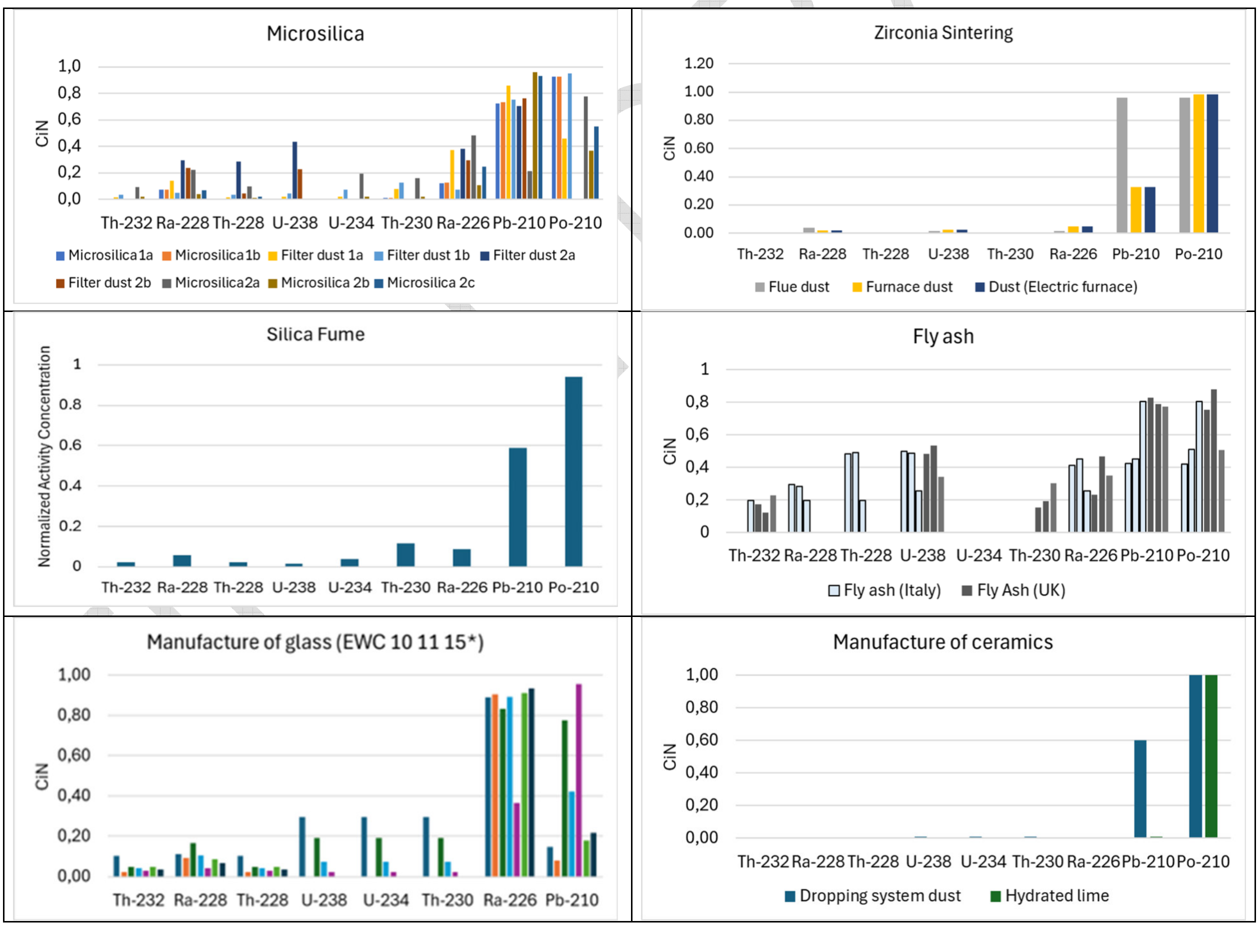


FIGURE 3-20: NORMALIZED RADIONUCLIDE COMPOSITIONS OF DUST FROM NON-METALLURGICAL PROCESSES

Note: Microsilica, Zirconia Sintering: unpublishes data of the authors. Silica Fume from [105]. Fly ash UK from [106], fly ash Italy from [107], [108]. Manufacture of glass: Wastes according to the European Waste Catalogue: 10 (from thermal processes) 11 (from manufacture of glass and glass products) 15* (Solid wastes from flue-gas treatment containing hazardous substances); Manufacture of ceramics [108].

3.10 How do industrial processes affect the activity concentrations of NORM?

3.10.1 What activity concentrations occur?

In Table 3-11 activity concentration ranges of NORM that occur in the industrial sectors listed in Table 3-1 are shown. Some values are taken from the literature and are referring to a cited publication. Other values are based on assessments and experiences and are given as an order of (half of a) magnitude. They define ranges that, to the authors' knowledge, are typical; however, they are not based on statistical analyses of datasets. Outliers that fall outside the ranges specified here in specific individual cases are therefore possible. It should also be noted that natural distributions are generally log-normal, and the maximum frequency therefore does not lie in the middle of the value range.

As far as not directly specified, the nuclides given in Table 3-11 are the dominant ones in the decay series.

The values given in Table 3-11 show the wide range of activity concentrations, starting with very low values of 0.01 Bq/g in ores and reaching up to 10,000 Bq/g in some scale deposits.

Except for niobium/tantalum, tin, and, to a lower extent, aluminum, the ores of these metals are radiologically unremarkable. Radiologically relevant materials may result from radionuclide concentration in slags or filter dust when they are processed.

TABLE 3-11: RANGES OF NORM ACTIVITY CONCENTRATIONS IN DIFFERENT INDUSTRIAL SECTORS. DATA NOT CITED WAS ASSESSED BY THE AUTHORS FROM DIFFERENT SOURCES

Industrial sector	Range in Bq/g	Dominant Nuclide	Comment
Extraction of rare earth elements	1 – 10	Th-232	Ores
	3 – 100	Th-232	Concentrates
Production of thorium and its compounds	1000 – 3000	Th-232	In thorium compounds
Production of niobium and ferro-niobium;	0.3 – 3	Th-232	Nb Ores
	5 – 50	Th-232	Tantalum Con-centrates [109]
	30 – 300	Th-232	Slag
Use of thorium and its compounds	10 – 300	Th-232	0.4 – 4 % ThO2
Mining of ores other than uranium ore	0.005 – 0.06	U-238, Th-232	Iron
	0.014	U-238, Ra-226	Iron imported to Japan [110]
	0.005	Th-232, Ra-228	
	0.03 – 1	Th-232, U-238	Aluminum (Bauxite)
	0.001 – 0.03	U-238, Th-232	Lead, Zinc
	3- 300	Th-232	Tin (Amang)
	0.1 - 3	U-238	P (sedimentary)
	0.01 – 0,03		P (magmatic)
Production of oil and gas	10 – 3000	Ra-226 (Ra-228)	Ra- Scales
	3 – 300	Ra-226 (Ra-228)	Ra-Sludges
	10 – 1000	Pb-210	Pb-incrustations
	1 – 300	Pb-210	Sludges
Manufacture of TiO_2 pigments		Th-232	

The phosphate industry	0.3 – 3	Ra-226	P-Gypsum [66]
The phosphate industry / DCP	Up to 10,000	Ra-226	Scale [98]
ammonium phosphate product.	Up to 1400	U-238	Scale [96]
Thermal P Production	Up to 1000	Pb-210	Dust [96]
The zircon and zirconia industries	0.5 - 5	U-238	
Production of tin, copper, aluminum, zinc, lead, and iron and steel	0.1 -1	U-238, Th-232	Red mud
	0.5 – 5		Tin slag (Amang)
			Copper slag
	0.1 – 0.3	U-238	Iron slag
	1 – 30	Pb-210	Blast furnace dust
Combustion of coal	0.01 – 0.1	U-238	Hard coal
	0.03 – 0.3	U-238	Bottom ash
	0.05 – 0.5	Pb-210, U-238	Fly ash
Water treatment	0.1 – 10	Ra-226	Filter sands
	1000	U-238	Ion exchange resin
Geothermal energy production	10 - 1000	Pb-210	Scales
	1 - 300	Ra-226	
Cement production and maintenance of clinker ovens	0.1 – 3	U-238	Refractory material
Building materials (including building materials manufactured from residues or by-products)	0.01 – 0.3	U-238, Th-232	

3.10.2 What is the reason for enhanced activity concentrations?

Activity concentration is the ratio of total activity (Bq) to a specific mass amount (g or kg). The higher the activity concentration, the more total activity there is in less mass.

High activity concentrations usually result in high external radiation dose rates and potentially high doses from inhalation or ingestion. Therefore, radiation protection must consider any material with a high activity concentration as a priority.

To determine how industrial processes affect the activity concentration of a specific material, a simplified model can be used (Figure 3-21). The basic quantities used to describe this process are the mass M and the activity A_r of a radionuclide *r* (unit: Bq).

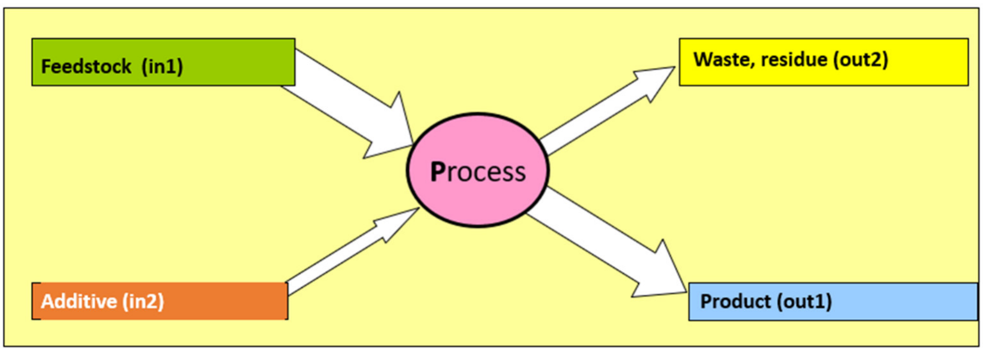


FIGURE 3-21: BALANCE MODEL OF A TWO-COMPONENT PROCESS (FROM [111])

Balance equations of masses and activities are

$$A_{r,in} = A_{r,in1} + A_{r,in2} = A_{r,out1} + A_{r,out2} = A_{r,out}$$ EQUATION 3-1

$$M_{in} = M_{in1} + M_{in2} = M_{out1} + M_{out2} = M_{out}$$ EQUATION 3-2

If these balances are written in a normalized form, the quotients on the right side of the equations can be interpreted as "transfer factors" ATF_r and MTF

$$1 = \frac{A_{r,out1}}{A_{r,in}} + \frac{A_{r,out2}}{A_{r,in}} = ATF_{r,1} + ATF_{r,2}$$ EQUATION 3-3

$$1 = \frac{M_{out1}}{M_{in}} + \frac{A_{r,out2}}{M_{in}} = MTF_1 + MTF_2$$ EQUATION 3-4

Any process that differs from pure mass transport splits the input into two (or more) fractions. These fractions can be interpreted as shares of the input mass or (total!) activity transferred to the components of the process output.

The activity concentration C of radionuclide r is the ratio

$$C_r = A_r / M_r$$ EQUATION 3-5

A concentration factor CF of radionuclide "r" can be defined as

$$CF_{r,1} = C_{r,out1}/C_{r,in} \quad \text{AND} \quad CF_{r,2} = C_{r,out2}/C_{r,in}$$ EQUATION 3-6

For many processes, the masses and total activities can be assumed to be present in the feedstock, with additives contributing only to a minor degree. With this assumption, the concentration factor in the output can be interpreted as

$$CF_{r,1} = \frac{ATF_{r,out1}}{MTF_{out,1}} \quad \text{AND} \quad CF_{r,2} = \frac{ATF_{r,out2}}{MTF_{out,2}}$$ EQUATION 3-7

Equations 3-7 mean that a high concentration of an output material results from a high activity transfer into a small mass. Vice versa, a low concentration of output results from a small amount of activity transferred into a large amount of mass. **Therefore, the splitting of masses sets the limits on the concentrations in the output materials.**

The diagram in Figure 3-22 shows the relation between mass transfer and concentration factor. It makes clear that high concentration factors are possible only if a small mass receives a significant portion of the total activity. Because the theoretical highest activity concentration in a waste material ("out 2") results if all activity of the input is completely transferred into the waste mass, the uppermost straight line with ATF2 = 1 is a borderline. Concentration factors above this line are impossible for balance reasons!

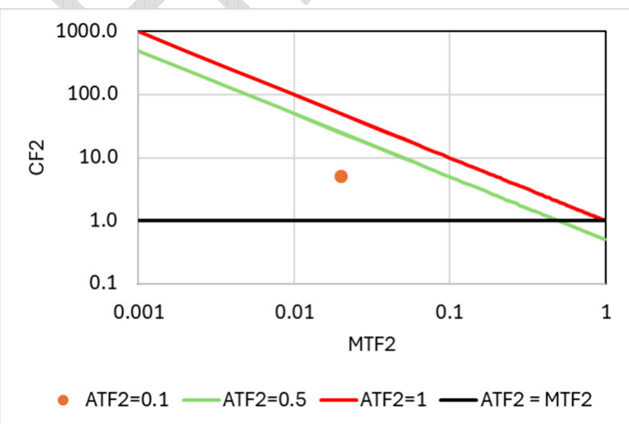


FIGURE 3-22: RELATIONSHIP BETWEEN MASS TRANSFER AND CONCENTRATION FACTOR (CF) FOR TWO DIFFERENT ACTIVITY TRANSFER FACTORS (ATF)

3.10.3 How do technical processes change the activity concentration?

In many technical processes, input materials are separated into various products, by-products, or waste. The model described in the previous Section has shown that any increase in activity concentration requires that a significant portion of the activity be transferred in a minor mass stream.

Two examples that demonstrate the application of the balance model are presented in Table 3-12 and Table 3-13.

The calculation in Table 3-12 demonstrates that the precipitation of a small amount of $BaSO_4$ (10 mg per kg) that takes 10% of the Ra-226 from a produced water will contain 100,000 Bq/kg (100 Bq/g) Ra-226. Table 3-13 is an example from a metallurgical process with a strong concentration of Pb-210 in dust, but also a smaller enhancement of concentration in the slag.

TABLE 3-12: EXEMPLARY CALCULATION OF RADIONUCLIDE CONCENTRATION IN HARD SCALES FROM OIL PRODUCTION

	Mass	Ba, Sr	Th-232	U-238	Ra-226
Concentrations "in"		**g/kg**	**Bq/kg**	**Bq/kg**	**Bq/kg**
Produced water (in1)		1.0	<1.0E-05	1.0E-03	10
Total amounts	**Kg**	**Gram**	**Bq**	**Bq**	**Bq**
Produced water (in1)	1	1	<1.0E-05	1.0E-03	10
Precipitated solids (out2)	0.00001	0.01	<1.0E-05	0.5E-04	1.0
Produced water (out1)	0.99999	0.99	<1.0E-05	9.5E-04	9.0
Concentrations "out"			**Bq/kg**	**Bq/kg**	**Bq/kg**
Precipitated solids (out2)	0.00001		<1	5	**100,000**
Produced water (out1)	0.99999		<1.0E-05	0.00095	9.0
Concentration Factor				**(--)**	**(--)**
CF Precipitated solid (Scale, out2)				5E+03	1E+04

TABLE 3-13: EXEMPLARY CALCULATION OF RADIONUCLIDE CONCENTRATION IN PIG IRON SMELTING

		Mass	Th-232	U-238	Pb-210
		Mg	**Bq/kg**	**Bq/kg**	**Bq/kg**
Input	Ore concentrates (in1)	600	20	20	20
	Coke, lime (in2)	60	10	10	10
	O_2 (Air)	40			
Output	Iron (out1	400	<1	<1	<1
	Slag (out2)	230	50	50	1
	Off-gas (CO_2; H_2O) (out3)	65	0	0	0
	Dust (out4)	5	1	1	**1,960**
Concentration factors			**(--)**	**(--)**	**(--)**
	CF iron (out1		< 0.05	<0.05	<0.05
	CF slag (out2)		**2.5**	**2.5**	**0.15**
	CF Off gas		0	0	0
	CF dust		0.05	0.05	98

The reasons behind these effects are that radionuclides are concentrated in the slag because smelting involves phase separation, during which a significant part of the mass is removed as metal, leaving the remaining mineral residues with the original radioactivity in a much smaller mass. Pb-210 and Po-210 in dust result from the vaporization of these radionuclides at high temperatures. Because Po-210 is the decay series radionuclide with the lowest evaporation temperature of 962°C, processes with temperatures exceeding 900°C are considered as high-temperature processes in this handbook.

A summary of activity transfer factors for NOR and analogous chemical elemental transfer factors (partitioning factors) in iron smelting and steelmaking processes is given in Table 3-14.

TABLE 3-14: ***ACTIVITY TRANSFER FACTORS FOR NOR AND CHEMICAL ELEMENTAL TRANSFER FACTORS (PARTITIONING FACTORS) IN IRON SMELTING AND STEELMAKING PROCESSES.***

Data steel, slag, dust from [112]

Element	Percentage Deportment (%)				Element	Percentage Deportment (%)			
	Steel	Slag	Dust	Off-gas	(NOR)	Steel	Slag	Dust	Off-gas
Fe	95 – 100	0 – 5	0 – 2		Pb	0 – 5	0 – 5	95 – 100	
Ni	95 - 100	0 – 1	0 – 2		Bi	0 – 25	0 – 25	45 – 100	
Co	20 - 100	0 – 1	0 – 80		Po	0 – 1	0 – 5	95 – 100	
H	0 – 10	0	0	100	Rn	0	0	0	100
C	27 – 100	0 – 1	0 – 2	0 – 73	Ra	0 – 5	95 – 100	0 – 5	
K	0 – 1	3 – 50	50 – 100		Ac	0 – 1	95 – 100	0 – 5	
Cs	0	0 – 5	95 – 100		Th	0 – 1	95 – 100	0 – 5	
Ba	0 – 1	95 – 100	0 – 5		Pa	0 – 1	95 – 100	0 – 5	
					U	0 – 1	95 – 100	0 – 5	

3.10.4 Special case: Coal combustion

The combustion of coal with naturally elevated levels of NOR results in significant NOR content in fly ash and bottom ash. If information about the radionuclide content is not communicated between the producer and the manufacturer, building materials may be produced that not only cause unnecessary external exposure but also act as a source of radon. Historical experience with such building materials exists, for example, in the Czech Republic and Sweden. These experiences contributed to the widespread implementation of measurements of NOR content in building materials.

Coal combustion releases sulfur primarily as sulfur dioxide (SO_2). Flue Gas Desulfurization (FGD) systems are employed in coal-fired power plants to reduce SO_2 emissions before flue gases are discharged to the atmosphere. The most widely applied technology is wet limestone - gypsum FGD, although semi-dry and dry processes also exist. FGD systems do not change the total radioactivity involved in the process, but introducing additional mass, usually free from NOR, can dilute the combustion products and additionally redistribute NOR among different solid residues.

Installation of FGD slightly reduces radionuclide concentrations in fly ash, because a fraction of volatile radionuclides (notably ^{210}Pb and ^{210}Po) partitions into the wet FGD slurry. Moreover, wet FGD systems preferentially accumulate radium isotopes (^{226}Ra, ^{228}Ra) due to chemical similarity between Ra^{2+} and Ca^{2+} and coprecipitation with calcium sulfate. As a result, FGD gypsum may show higher Ra activity concentrations than fly ash, however uranium and thorium remain largely insoluble and are less affected by the process.

While FGD does not generate additional radioactivity, it alters the partitioning of naturally occurring radionuclides, shifting radium and lead isotopes from fly ash into FGD residues, thereby modifying the radiological characteristics of combustion byproducts. Regardless of the main objective of its application, FGD can be considered as a waste prevention if controlled from this perspective. On the other hand, an increased amount of NOR can limit FGD residues reuse in building materials production, for example. Hence again, careful consideration of the whole process is necessary.

3.11 In which industrial processes are NORM deliberately used?

3.11.1 Refractory and abrasive materials

Refractories and abrasives are widely used in industrial production. Many of the substances that the refractories or abrasives are made from are low in radioactivity. However, some typical raw materials used to produce refractories or abrasives result in enhanced activity concentrations. These materials are bauxite used for making corundum and zirconia.

Because the enhanced radioactivity of zirconia has been well known for many years, information from the producer to the consumer about the radioactivity should be part of good radiation protection. Such information can be submitted via safety data sheets, which are common in the industry. Within such established practices, the use of "radioactive" products must be considered deliberate. Therefore, exposure due to working with such products is planned and accepted.

3.11.2 Thoriated products

Uranium and thorium are used in some industries because of their physical and chemical properties outside nuclear technologies. Examples include thoriated gas mantles, thoriated magnesium alloys for aircraft turbines, thoriated infrared optics, uranium-containing trimming weights in aircraft, uranium-metal shielding containers, and uranium glasses.

An essential sector where thorium plays a significant role is the use of tungsten metal alloys. Because thorium improves the capability of electron emissions, thoriated components are used in lamp production as

- thoriated tungsten electrodes or electrode coatings,
- ThO_2 sintered bodies as electrode inserts,
- Thorium metal foils as electrode components,
- ThJ_4-containing filling substances.

Furthermore, thoriated tungsten alloys are used as

- welding electrodes,
- components (e.g. nozzles) for special machines.

The thorium content of tungsten alloys varies. Additions of 0.35-0.55% (WT4), 0.8-1.2% (WT10, F288 Type 2A), 1.7-2.2% (WT20, F288 Type 2B), 2.8-3.2% (WT30) and 3.8-4.2% (WT40) are common. The %-values refer to the added amount of ThO_2, not elemental thorium.

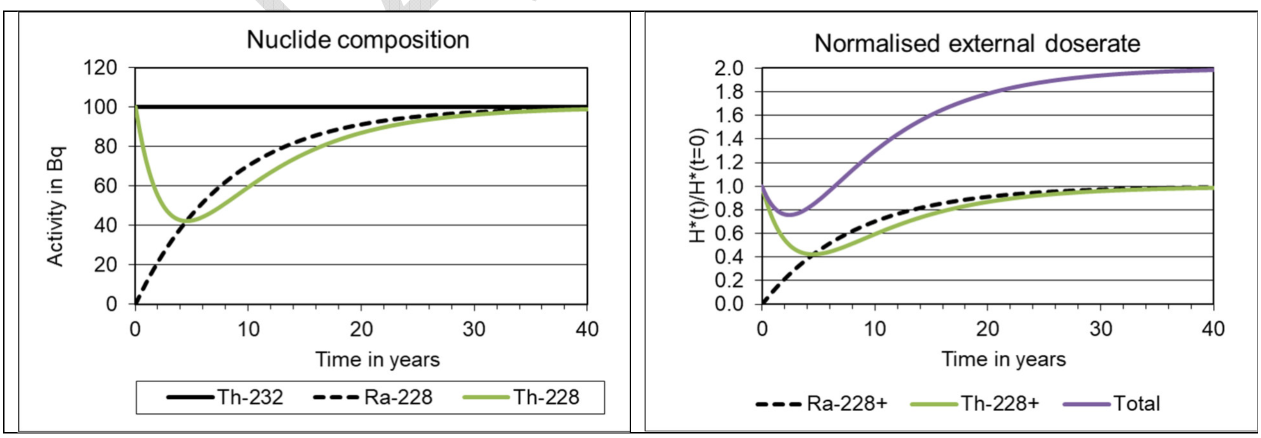
Since thorium is firmly enclosed in tungsten electrodes, only external exposure occurs when handling such parts. The annual dose is therefore low.

Higher exposures are possible during the manufacture of alloys and during welding. In these cases, thorium-contaminated dust may occur and result in internal exposure,

Note: As we stated in Section 2.3.6, the radiologically relevant radionuclides of the Th-232 series are Th-232 (forming the chemical element thorium), Ra-228 (with Ac-228 as a significant gamma emitter) and Th-228 with its series of decay products, including the gamma emitters Bi-212 and Tl-208.

Unlike uranium, the nuclide composition of the daughter nuclides, and thus also the dose rates in thoriated materials and the total dose coefficients for inhalation and ingestion, change significantly in the first years after the chemical manufacture of thorium compounds (commonly used are thorium oxide or thorium nitrate). Immediately after chemical separation, thorium consists of the two isotopes Th-232 and Th-228, which are in activity equilibrium, as well as a (usually small) proportion of Th-230 from the U-238 decay series. At this point, the physical activity is twice that of Th-232 (2*Th-232) + a proportion of Th-230 (assumed to be 20% of Th-232). According to radioactive decay laws, the activity of Ra-228 increases with a half-life of 5.7 years, and Th-228 decays with a half-life of 1.9 years. Since the dose rate is determined by Ac-228 (daughter of Ra-228) and Bi-212, Tl-208 (daughter nuclides of Th-228, Ra-224), the dose rate of thoriated objects changes over time. It reaches its minimum approximately 3 years after the primary manufacture of the thorium compounds (see Figure 3-23).

Because the inhalation and ingestion dose coefficient of the radionuclide mixture in a thoriated object is the sum of the three radionuclides Th-232, Ra-228 and Th-228 (short-lived decay products are included because of the committed dose approach). In Figure 3-23, the temporal changes of the total dose coefficients of chemically separated thorium are shown. Due to the dominance of Th-232, temporal changes in inhalation are low, whereas for ingestion, the supremacy of Ra-228 results in a significant increase over time.



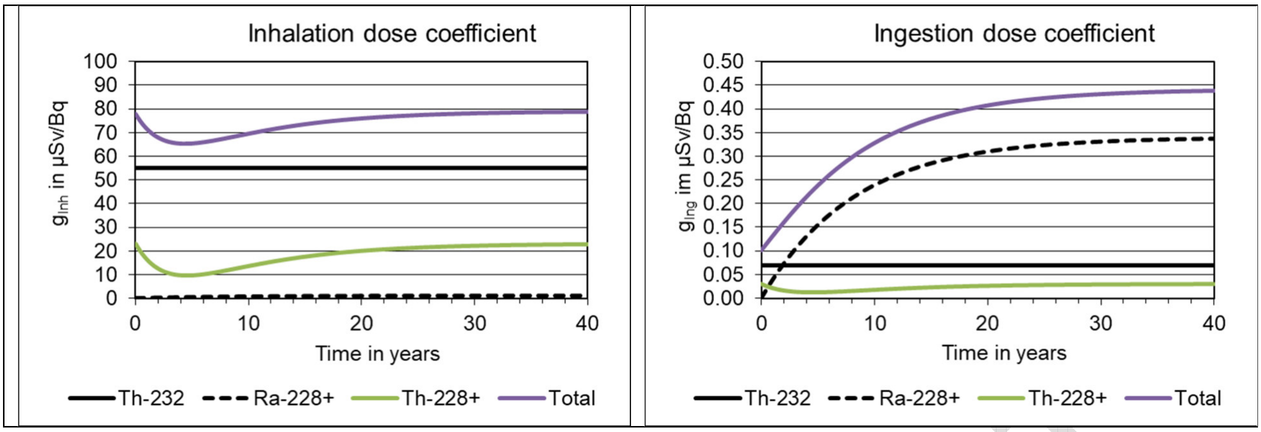


FIGURE 3-23: TEMPORAL CHANGES OF THE RADIONUCLIDE COMPOSITION, THE EXTERNAL RADIATION AND THE TOTAL DOSE COEFFICIENTS FOR INHALATION AND INGESTION FOR WORKERS

3.11.3 Special case: potassium-40

Potassium salts are an essential raw material in the chemical industry. Many potassium salts used in industry contain more than 30% potassium and thus have activity concentrations exceeding 10 Bq/g. In Table 3-15 these salts and their primary purpose are compiled.

TABLE 3-15: POTASSIUM SALTS WITH K-40 EXCEEDING THE EXEMPTION VALUE, AND THEIR PRIMARY PURPOSE IN THE INDUSTRY

Formula	**Name**	**Molar Mass [g]**	**C_{K-40} [Bq/g]**	**Primary purpose (from Wikipedia)**
K_2O	Potassium oxide	94,2	25,9	
KCl	Sylvine (Mineral)	74,6	16,4	Fertilizer
KOH	Potassium hydroxide	56,1	21,7	Detergent production, microsystems technology: etching of Si; food industry (acidity regulator); glass industry, ...
K_2CO_3	Potash	138,2	17,7	Glass industry, paint production, soft soaps
KF	Carobbit (Mineral)	58,1	21,0	Chemical industry; enamel production,
KNO_3	Saltpetre	101,1	12,1	pickling salt; fireworks
K_2SO_4	Potassium sulphate	174,2	14,0	Fertilizer, extinguishing powder, production of synthetic rubber, food additive (E515)
K_3PO_4	Potassium phosphate	212,3	17,2	Detergents, food additive (E340)

Although many potassium salts are used in large quantities, they are often not monitored as strictly as other NORM. However, problems can arise when products containing potassium salts trigger radiation alarms at portal measuring systems during export, import or disposal. As the radiological risk posed by these salts is limited, practitioners should contribute to an effective solution in such cases by carrying out an appropriate assessment.

A specific case is the use of potassium salts in consumer goods, including food additives. Some explanations regarding this are given in Chapter 10.

3.12 Which other industrial products with NOR exceeding the exemption values are known?

Other industrial products with NOR that, in individual cases, may exceed the exemption values, are summarized in Table 3-16. One reason for metal contamination is the physical and chemical similarity of the feedstock; another may be the recycling of a feedstock with low metal content. Examples are described in Chapter 7.

Consumer products with elevated NOR levels are described in Chapter 10.

Laboratories or research institutes that use uranium or thorium compounds for analytical purposes are not considered an industry in this handbook.

TABLE 3-16: EXAMPLES OF PRODUCTS WITH NOR ACTIVITY CONCENTRATIONS EXCEEDING THE GENERAL BACKGROUND LEVEL

Product	Radionuclide	Remarks
P-fertilizer	U-238+ (U-234)	from sedimentary P-rock
Lead metal	Pb-210+	especially in solder
Lanthanum ingots	Ac-227+	Only in exceptional cases. Caused by the processing of low-grade ores or byproducts
Titanium metal	Th-232	Only in exceptional cases. Probably caused by recycling

3.13 Helpful tips

- Know where the radionuclides are introduced in the process – but be aware: low activity concentration in the input will not guarantee low activity concentrations in output materials or in contaminations of the facilities.
- Have a good understanding of the physical, chemical, and thermal processes that are occurring in the operation.
- Apply the basics to understand how radionuclide patterns may be modified in the processes.
- Have special attention to processes that generate small amounts of mass compared to the total mass streams (e.g., incrustations in facility components).
- Have a good understanding of the radioactive properties of the raw materials, the products, and the wastes.
- Communicate with technical people in the company who will understand the processes.

4 GRADED APPROACH (GA) TO NORM

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4.1 The GA in Context

Historically, many industrial practices have standard industrial hygiene measures which act to control worker exposures to contaminants such as airborne dust and hazardous chemicals. When some of these practices identify the presence of NORM, the measures have had to be adopted. In its Publication 104 [113], the ICRP recognized that industries involving NORM have been subject to variable regulation because specific controls for radiation have had to be retrofitted.

It is important to ensure that the controls for radiation are commensurate with the risk, and this is the basis of the GA.

Regulatory mechanisms such as exemption and exclusion have been used in some cases, and in other cases, more prescriptive measures have been implemented (such as the requirements for PES when an activity concentration exceeds a certain level).

Application of a standard GA, where controls and regulations should be commensurate with risk, has been difficult. This is because the GA requires assessment and judgement, which can be complex and subjective.

This chapter of the handbook provides some broad philosophical and practical advice on the application of the GA. It is important to remember that approaches can vary based on many factors, such as the type of activities and practices, the competency of the industry and the regulator, and the maturity of the regulatory system.

The ICRP, in Publication 104 recommended a **graded approach (GA)** in the management of NORM exposure, taking into account the prevailing circumstances and risk to people, with the global aim of promoting the protection of workers and public health ([113] Para. 137; [114para. 9].

At its core, the GA is a means of varying the stringency of application of the requirements of radiation protection in accordance with the industry, situation and circumstances of exposure. It takes into account:

- The characteristics of a facility or activity and operational procedures according to the safety significance and complexity.
- The potential impacts of the facility or activity on human life and health and the environment.
- The possible consequences of an unanticipated event or an activity improperly carried out.

One of the underpinning principles of radiation protection (as described by the ICRP) is that of "justification", where the benefits exceed or balance the costs. This is important when considering industries and operations with NORM. Unnecessary controls could inadvertently hamper legitimate activities. Therefore, a RP regulatory system in industries involving NORM should be graded, with regulations that are justified.

The benefit of the GA is that it takes into account limited resources and ensures that those resources are focused on what matters.

In industrial practices, the GA exists on two levels:

1. A proportionate implementation of RP regulations by the authorities;
2. An organization with operational RP that complies with occupational protection, environmental, and waste requirements.

In practice, the GA works when there is a positive link between the proportionate requirements and the implementation of those requirements.

4.2 Why do we need a GA?

Key characteristics of industries involving NORM are:

- the source material (NORM) is not deliberately introduced in the industrial process for its radioactive properties,
- there are no real prospects of emergencies leading to fission events or acute tissue reactions, due to the relatively low levels of radiation exposure and low concentrations of radionuclides routinely encountered,
- occupational and public exposures can be anticipated, but their level cannot be confirmed without a characterization, and the results of such a characterisation may be highly variable,
- potentially high cost of regulation (and liability) in relation to reduction in exposure.
- Industries involving NORM must manage multiple hazards and pollutants.

Handling this complex interplay of different characteristics requires consideration of established occupational protection procedures, additional costs of controls, handling of large volume/low activity concentration materials and the emotions and perspectives and experiences of all involved stakeholders.

In addition to the radiation-related aspects, most industries have other health and safety hazards and risks that need to be managed. Maintaining all hazards and risks in perspective requires an "**integrated approach**" to occupational health and safety. An extension to this is a **holistic approach** which additionally includes the environment, the economy, emotions and perspectives. This overall approach is shown in Figure 9-2.

To avoid misunderstanding, we note that both terms are used in this handbook from a practitioner's perspective. This means that practitioners should be aware of the effects, requirements, and challenges associated with chemical toxic substances under common occupational protection. Moreover, we also should keep in mind that radioactivity is a term that creates emotions (frequently fear) that may result in decisions that result in additional cost without reducing any dose. Our perspective in the handbook is not a regulator´s perspective. The question of whether both approaches should be regulated is outside the scope of this handbook.

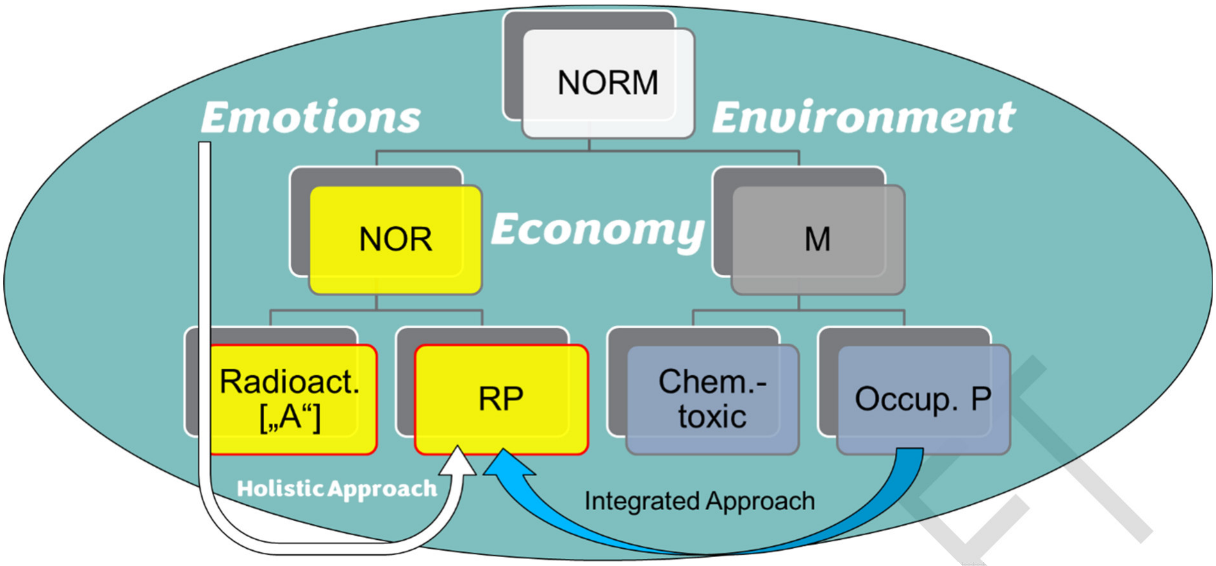

FIGURE 4-1: THE NORM-SYSTEM WITH INTEGRATED AND HOLISTIC APPROACH

To manage this complex system and its many challenges, an appropriate system of control is needed, which incorporates a **graded approach** to overall protection. This ensures that the measure for radiation protection are consistent with the size of the overall hazard (or risk) and that unnecessary burdens are not imposed.

There are many cases where a previously acceptable practice is shunned simply because of very low levels of radioactivity or the presence of NORM. Regulatory constraints by way of additional controls or license conditions means that is some cases, the practice is not financially viable and abandoned.

In this handbook, we do not say that NORM is irrelevant. We just say that decision-making should be based on actual risks and that unnecessary and unjustified imposition of requirements should be considered very carefully, noting the potential impact on the financial viability of the operation and the stakeholders (mainly employees).

Therefore, RP in industries involving NORM should be established in a manner commensurate with the radiation risks, avoiding overregulation. Regulations and the implementation of regulatory requirements should be done in a graded manner.

In industries associated with NORM, radiation accidents with fatal consequences from acute radiation exposure do not occur and can be excluded. However, it is important to know the distribution of individual doses for the different tasks and different industries and the exposure pathways. This avoids the situation where doses are potentially high and (although not immediately dangerous). Moreover, the fact that industry is a multi-hazard situation, where radiation is only one of a number of hazards (and generally not the dominant one) implies the need of a GA strategy for control.

A key objective of RP in industries, is optimization. RP is directed to keep exposures as low as reasonably achievable, taking social and economic issues into account. A method that helps find ways to implement the ALARA principle is the GA. Optimization should be implemented in a holistic way, taking into account all hazards and applying reasonable, practical and prudent actions.

4.3 How Does the GA Exist in the International Standards?

The GA is an essential part of the system of protection and is extensively covered in the IAEA Safety Standards. In 2016, the IAEA published General Safety Requirements (GSR) Part 1: Governmental, Legal and Regulatory Framework for Safety [115] on the essential aspects of the framework for establishing a regulatory body and taking other actions necessary to ensure the effective regulatory control of facilities and activities utilized for peaceful purposes. These GSR states

> "*The regulatory body shall structure its organization and manage its resources so as to discharge its responsibilities and perform its functions effectively; this shall be accomplished in a manner commensurate with the radiation risks associated with facilities and activities. The performance of regulatory functions shall be commensurate with the radiation risks associated with facilities and activities, taking into account national circumstances, in accordance with a graded approach*."

In 2014, the IAEA published the General Safety Requirements Part 3: Radiation Protection and Safety of Radiation Sources, often referred to simply as the Basic Safety Standard ("the BSS") [116], jointly sponsored by eight international organizations with responsibilities in various areas of radiation protection. This publication provides a definition for GA[11] and states

> *"authorities shall adopt a GA to the implementation of the system of protection and safety, such that the application of regulatory requirements is commensurate with the radiation risks associated with the exposure situation."*

The requirements in the BSS take account of the most recent scientific evidence relating to exposure due to radiation. The BSS is used by many countries as the basis for their national regulations.

Determining the most appropriate regulatory framework to carry out regulatory body's activities and optimize the available resources can be challenging. In addition, implementing a GA in the regulations can be difficult due to lack of experience. However, this will improve over time as the regulatory bodies gather knowledge from lessons learned and collective experiences.

The development of a more systematic and complex GA model requires a deeper understanding of the industries, the industrial processes and potential exposure pathways. Consideration of historical data of worker and public doses for normal and potential exposure situations broadens the understanding. An important mechanism is an ongoing review of the effectiveness of controls and performance leading to continuous improvement.

ICRP recommends a GA applied to industries with NORM in its publication 142, so that efforts and resources expended on controls, monitoring and protection are commensurate with the radiological hazards and risks. This means that the regulation is balanced with the benefits of the industry. Conversely, facilities are required to ensure that they behave appropriately to limit impact and liability (e.g., surface and groundwater discharges, effluents to air).

[11] Graded approach: For a system of control, such as a regulatory system or a safety system, a process or method in which the stringency of the control measures and conditions to be applied is commensurate, to the extent practicable, with the likelihood and possible consequences of, and the level of risk associated with, a loss of control.

4.4 What does applying the GA mean?

The components of a GA include:

- A good understanding of the operation, facility and the processes being used. See Chapters 2 and 3 for some references for assistance.
- Understanding the activity of materials throughout the processing and the potential exposure pathways. See Chapter 5.
- Understanding of the protection in practice and its effectiveness. Chapter 4 gives comments on this.
- Considering all radiation risks associated with facilities and practices. Basics for this are described in Chapter 2.
- A balanced and appropriate regulatory system that focusses on controlling the actual risks. See Section 4.5 for additional discussion.

4.5 How to develop a GA in regulations?

A robust and fit for purpose regulatory system incorporates the following features:

- Focusing regulatory functions on specific higher-risk activities or practices.
- Ensuring that regulatory requirements should be proportionate.
- Ensuring that regulatory and operational resources are optimized.

As described previously, the IAEA has developed international RP Standards, which are based on a GA with different regulatory control levels proportionate to the risk. These can be used as the basis for a first set of regulations.

Worldwide, most national legal frameworks are based on the IAEA Standards. However, it is important to keep in mind that, in many countries, the industries involving NORM are regulated/controlled by different authorities (radiation protection authority, mining regulator, environmental authorities, health authorities…). So, it is necessary to work collaboratively between authorities to clearly define the responsibilities of the different involved authorities.

A common understanding of the risks and the necessary requirements enables a ranking of the various industrial sectors (see chapter 4.1) depending on the likelihood of risk and the magnitude of exposures. This ranking may take into account the risks for workers, members of the public, or both, based on national and international background for workers and the environment[12]. In the case of environmental impact assessments, regulators can consider previous the assessments or those already performed by Environmental Authorities.

A recognized practical method for exempting industries or practices involving NORM from regulatory control is based on the generic clearance values established by IAEA for natural radionuclides in terms of Bq/g (1Bq/g for all naturally occurring radionuclides apart from K40 which is 10 Bq/g).

The other regulatory criteria is based on "risk", such as dose levels or dose constraints for workers or members of the public. In terms of the dose criteria, the exemption for bulk material

[12] Environment includes humans (i.e. members of the pubic) and ecosystems.

containing natural radionuclides is a value of the order of 1mSv/y, to any individual (worker or member of the public exposed). The dose criterion should be interpreted as being the dose increment resulting from the practice (i.e. not including the dose from local natural background radiation, or the dose as a result of exposure to radon). It is relevant to note that in IAEA GSG 17, the phrase "of the order of 1 mSv" is used. In some countries, this is interpreted as including doses in the range 1–3 mSv.

When the radioactivity occurring in industrial processes cannot be exempted, a regulatory control system needs to be established and utilized. Without a graded approach, it is difficult to ensure that resources are efficiently and effectively optimized.

Within the current system of radiological protection, exposure situations are classified as 'existing', 'planned', or 'emergency' (Section 2.3.3). This can sometimes be confusing when it comes to NORM. However, NORM exposures in industrial processes are highly unlikely to result in acute tissue reactions and will not warrant an emergency intervention or action. (Note that spills of radioactive materials, including tailings dams failures, or releases or radioactive liquors to waterways, may cause physical damage or chemical damage; however, radiological impacts are generally minor and not considered to be radiological emergencies in the exposure situation context).

For NORM, potential impacts are probabilistic (stochastic) and not immediately observable effects. Therefore, RP for NORM are considered to be Existing Exposure Situations (EES) or Planned Exposure Situations (PES).

Practical experience has shown that RP for NORM is not regulated consistently across the world. In some countries it is managed as a EES and in others it is managed as a PES. As shown elsewhere in this handbook, the radiation protection for EES and PES are different, which causes confusion around the world. This is also the case of radon exposures, which is based on national determinations [117].

While a 'GA' is recommended as part of the regulatory system, justification of the practice, together with optimization of the protection may simply be sufficient. Reference levels (as recommended for EES in ICRP 142) can be used to monitor performance.

Despite the differing requirements for EES and PES, it is important to note that the regulatory system should not necessarily be bound by the strict application of either the EES or PES requirements. In all cases, optimization of exposures underlies good radiation protection management.

As noted elsewhere, the levels of regulatory control for "planned exposure situations" are; exemption, notification, registration and authorization and this approach can be used. Regardless of the approach and exposure situation, the following steps have proven to be worthwhile for establishing a foundation for practical regulation of industries with NORM:

Step 1: **Radiological assessment**

A list of industrial processes may be defined in advance by the legislator to be included in the scope of regulations. In other cases, NORM-related activities not included in advance could be identified, either based on experience or what occurs elsewhere. Authority remains with the regulator to add to its regulatory coverage if warranted. In all cases, it is important to perform comprehensive characterization (including all aspects covered in the system in Figure 4-1) in order to understand the hazards and associated risks involved. A screening criterion can be used at this step to identify and segregate practices based on radioactive activities or materials. The aim is to identify those practices that do not require additional radiological requirements and focus resources on those that do.

Step 2: Application of justification and optimization principles

Following characterization, the justification and optimization principles are applied to the practices. The characterization forms the basis for the process of justification of a planned practice, whereby decisions can be made based on the radiological properties of the industry or the practice. (Note that generally, radiation-related aspects may not have been included in early decision-making for many existing operations). The justification might be part of a broader assessment of the practices which considers a range of non-radiation related aspects.

Regarding NORM it is important to know that the concept of justification in radiation protection has a different meaning when applied for planned or existing exposure situations! If NORM is considered an existing exposure situation, the justification refers to the protection strategy not to the practice (or industrial process). See Box 4-1.

BOX 4-1: JUSTIFICATION OF THE PRACTICE OR JUSTIFICATION OF THE PROTECTION STRATEGY?

The concept of justification in radiation protection has a different meaning when applied for planned or existing exposure situation:

- For planned exposure situation: the *practice* needs to be justified (here e.g., the practice of incorporating NOR deliberately in consumer products);
- **For existing exposure situation: the *protection strategy* needs to be justified.**

These two different meanings overlap each other: suppose a shipment of consumer goods containing NORM is accidentally detected through a portal monitor. This is an existing exposure situation where different protection strategies may be considered:

- Do nothing.
- Recall all products already distributed and destroy them.
- Ship the products back to the producer and request the producer to adapt its manufacturing process to minimize the NORM content.
- (apply other feasible options).

In the 3rd strategy, what was an existing exposure situation becomes a planned exposure situation where the producer may act on the manufacturing process and may need to justify the use of NORM in its products.

Justification is a complex process as it addresses societal aspects. As mentioned in IAEA requirement 3.17, "frivolous" use of radioactive substances is prohibited, but the exact extent and meaning of "frivolous" may be subjective, has evolved with time, and may depend on national circumstances.

In existing exposure situations involving consumer goods, the question of justification of the protection strategy may be complex. For instance, which protection strategy (if any) should be applied to buildings or public spaces covered with uranium-glazed tiles? Such a decision would need to consider a mix of radiation protection considerations (assessing the dose-impact of these tiles [4]), cost (removing the tiles and managing them as waste), cultural heritage[13], public perception, etc. (see Chapter 10).

[13] In Australia for instance, a public petition to "protect Australia's historic uranium tiles" has been launched on the internet: https://www.change.org/p/protect-australia-s-historic-uranium-tiles

Once justified, the process of optimization occurs where controls are iteratively implemented to achieve an exposure or dose level that is considered to be acceptable. Importantly, this step should be undertaken in a holistic manner, taking into account other hazards. An important note is that justification of NORM practices is inherently different to justification on nuclear practices. This is because the levels of risk are vastly different.

As part of the optimization assessment, reference levels may be used to indicate that optimization "has been achieved". These can be used to guide performance and include dose criteria and /or material activity concentration values (in order to decide on exemption and or clearance). To verify compliance with dose reference levels, dose assessments need to be performed. A graded approach suggests starting with a screening dose assessment based on conservative assumptions. If verification of compliance is not accomplished, then a more detailed dose assessment with site-specific parameters can be done. If compliance is not achieved with a more detailed assessment, it will be necessary to apply stricter controls may be appropriate (see below).

Note also that IAEA GSG 17 [118] in the context of an EES, exemption can be applied via an "exemption-like process". Since there are so many possible exposure scenarios across various industries, flexibility and optimization are important when applying the GA.

Step 3: Applying the necessary requirements of PES

When stricter controls are deemed to be necessary, some of the IAEA defined radiation protection requirements for a PES can be used (see GSR Part 3). For NORM situations, it is appropriate to consider each of these requirements to see if they are applicable or useful for the industry or a particular practice. These requirements can become conditions on a permit or radioactive materials license, which is subject to enforcement.

Regardless of the exposure situation (EES or PES), the optimization principle shall always be applied.

Consultation with relevant stakeholders early in the optimization process will contribute to selecting the best options for control and management. It may seem contentious, however, maximizing knowledge into decision making leads to better decisions. However, it is ultimately the responsibility of the regulator to establish the requirements.

4.6 How to establish the GA in operational processes?

Industries involving NORM are familiar with management frameworks for conventional hazards and risks. Therefore, authorities should ensure that an holistic approach to the health and safety program of the facility incorporates the radiological risk, and other risks in perspective. Indeed, the radiological risk is generally not the most important.

For the operator of a facility, the GA to protection should first take account of the existing knowledge and experience of similar industries where similar hazards and risks are managed. It is then appropriate to integrate measures for the management of radiological protection.

The GA must start with a characterization of the radiation and exposure levels (via baseline or prior radiological assessment). This characterization may be based on a documentary basis (national or international background) and incorporate existing or other measurements in the facility.

The baseline or prior radiological assessment should include:

- the type of process/nature of work,
- the characteristics of the exposure to ionizing radiation,
- the frequency of exposure,
- the effective dose or the equivalent dose that the worker is likely to receive over the next twelve consecutive months:
  - taking into account all the exposure pathways excluding radon,
  - taking into account potential exposures and reasonably foreseeable incidents inherent to the workplace,
- the effective dose exclusively related to radon that the worker is likely to receive over the next twelve consecutive months,
- the interaction with other risks (physical, chemical, biological and/or organizational risks) of the workplace.
- The conventional protection already in place.
- The effective dose that the public is likely to receive, including analysis of exposure pathways.

If there is a potential risk, measurements of the workplace and of the environment are required (i.e., a radiological characterization of NORM is needed, including sampling and laboratory measurements of the different materials involved in the process, in situ measurements techniques as gamma in situ, dose rate measurements and radon measurements in the workplace, and measurements in environmental matrices). The results of these measurements must be compared to reference levels. The reference levels could be established in terms of dose levels, or activity concentration levels (i.e., for radon).

Various provisions for controls are outlined below.

- Consideration of "collective dose reduction measures" resulting in a reduction in doses to a large cohort of workers (e.g., area reduction through shielding or time limits). If doses are high, the other more specific provisions as described in IAEA BSS [116] may apply as relevant.
- The need for a qualified worker for radiation protection officer (RPO) should be graded, depending on the characteristics of the process, the operations, and the risks involved. In some cases, the person in charge of Conventional Safety (occupational hygiene and safety) can take on radiation protection with appropriate training. Different levels of training based on responsibilities are part of the GA.
- Any installed engineering controls and administrative controls should be checked for effectiveness.
- Consideration needs to be given to waste and residue generation, where NORM levels may be elevated for example, tailings, smelting filters,
- Consideration should also be given to maintenance activities.
- Regular inspections should be undertaken and be proportionate to the radiological hazards and risks. For example:
  - for industries where there is a real radiological risk, the frequency of the inspections may be annual.
  - for industries where there is a potential radiological risk, the frequency may be every 2 or 5 years.

  - for industries where there is an unlikely radiological risk, the inspection may be conducted only when there is a modification in the plant.
- Inspections may focus on the management of the radiological risk for workers, the public and for the environment:[14]
  - In case of industries where there is a (real or potential) radiological risk for workers, the first inspection may focus on the prior radiological assessment, and then, for the following inspections, the inspections may require modification of the radiation protection program. Note that depending upon the way that a practice is regulated (PES or EES), there may be differing compliance requirements.
  - In case of industries where there is a (real or potential) radiological risk for environment, the topic of the inspections may include the discharges monitoring and the environmental monitoring practices.

Chapter 6 gives more detailed information about the content of an inspection.

Implementation of the GA is a shared responsibility between regulatory bodies, owners, operators and RP experts.

4.7 How radon can be considered in the GA?

In workplaces, radon (and thoron where appropriate) should be managed using reference levels expressed in radon exposure (WL; Bq h/m^3), air concentration levels (Bq/m^3 Rn-222) or concentration of progeny (mJ·/m^3) established by national authorities. The decay series of radon and thoron are different, and the measurement of the decay products is also different from that of radon[15]. Care must be taken when considering these factors in a measurement protocol. When concentration levels still exceed the reference level following the application of radon prevention and mitigation measures, it may then be necessary, within a GA, to perform additional assessments of exposure in terms of dose. In such a case, a reference level of the order of 10 mSv per year recommended by ICRP could be used, bearing in mind that other values are used, for example, in the European Union, the value is 6 mSv per year. If the dose associated with radon or thoron exposure cannot be reduced below the reference level expressed in dose, the relevant requirements for occupational exposure apply, and their exposure should be managed using the relevant radiological protection requirements established for occupational dose (ICRP 126-ICRP 142). In these situations, the total effective dose for the workers must be considered (including the dose from radon) against the appropriate dose limit (noting that dose limits may vary from country to country).

The steps for applying a GA for implementing radon protective actions in workplaces can include:

a) Ensuring adequate controls are in place in all workplaces
b) Optimizing protection using a derived reference level for workplaces

[14] It should be noted that these frequencies may be similar to that of licensed activities of similar hazard and risk under a PES.
[15] Since thoron has a 55-second half life, its measurement should be made close to the source, whereas the decay product of concern has a long half-life and should be measured in the breathing zone.

c) Optimizing protection using the actual parameters of the exposure situation, such as occupancy, to verify the reference level selected; and
d) Applying the relevant requirements for occupational exposure, even dose limits, when, despite all reasonable efforts, the exposure remains above the dose reference level.

The relevant requirements for occupational exposure (for example the requirements of a Planned Exposure Situation) apply in workplaces where, from the outset, exposures of workers to radon are considered as occupational by national authorities.

The occupational dose limit should apply when the national authorities consider that radon exposure situation should be managed as a planned exposure situation.

4.8 How to apply GA in waste and residue management?

A diversity of industries generates NORM residues and waste, which should be managed in a safe, and sustainable manner.

A GA for the protection of the public and environment (e.g., biota other than humans) from NORM residues and wastes includes (cf. Chapter 7):

a) waste prevention (assessing the potential for generating different types of residues, based on the design and operation of similar facilities, considering different feedstocks),
b) waste minimization (measures to control the generation of residues,
c) processing (sorting, characterization, segregation, and treatment), developing an inventory of concentrations, volumes of residuals, and amounts of effluents and discharges,
d) reuse and recycling,
e) long-term management including; incineration, injection, disposal (in a conventional landfill, a facility for NORM waste, or a radioactive waste disposal facility).

Not all NORM waste is considered radioactive waste under many countries' laws. In some cases, it is a solid waste containing radioactivity not associated with the nuclear fuel cycle. This means that the material can be handled under environmental regulations using permits rather than licenses and provides more opportunity for safe and economic alternatives to disposal in a radioactive waste facility. In other cases, it is classified as radioactive waste and attracts nuclear regulation and control.

Some NORM residuals can (and are) reused and recycled, and this trend will likely continue as society moves to more sustainable uses of resources, in accordance with the United Nations Sustainable Development Goals (for example, moving from a linear to a more circular economy). However, this desirable process is frequently hampered by formal application of exemption values without considering the (very low) doses that could be occurring [119].

In all cases of NORM residues and waste management, a focus should always be on the promotion of the application of generic and clearance levels based on dose estimations.

Incineration or disposal in conventional landfill, landfill dedicated to NORM waste or radio-active waste disposal facilities, is usually based on activity concentrations. To do this, regulators can establish generic clearance values, and conditional clearance values based on dose estimations which enable guidance on how the NORM waste can be treated (for example as a conventional waste or as a radioactive waste). This allows optimization of economic and human resources and avoids final disposal as radioactive waste, when this is not necessary.

Some jurisdictions evaluate the disposal facilities', construction and modelling results based on local geology, hydrology, etc., and develop site-specific waste acceptance values for each facility, often much higher than generic limits (particularly in dry climates).

Be careful: The chemical characteristics (non-radiological hazard) of the residues/waste are usually dominant and must be taken into account in the residue/waste management. Again, an integrated approach to hazard and risk analysis is recommended throughout the process.

4.9 Discharges from industries with NORM and the GA

Liquid and gaseous radioactive and/or non-radioactive effluents are discharged deliberately from the routine operation of industries involving NORM. Effluents and emissions should be properly controlled, taking into account the radiological and non-radiological impacts and, if necessary, restricted in order to protect the public and the environment. In some countries, environmental laws will regulate specific emissions or discharges under air pollution or surface or groundwater discharge permits. However, many older jurisdictions did not include NORM in their discharge permits. In these cases, it is important that current regulators communicate with each other to ensure that all hazards and risks are properly considered. For example, the regulation of oil and gas facilities should also include consideration of NORM accumulation in waste and residue streams. Similarly, some "non obvious" mining residues may contain elevated concentrations of NORM.

If there are discharge pathways to local human receptors, then measurements and modelling (using appropriate software) should be conducted to evaluate radiological and non radiological emissions on nearby receptors. This may involve the need for complex terrain modelling in some cases. The optimization process should also consider protection of the environment. The aim is to avoid deleterious effects on non-human species. Such an approach should be commensurate with the overall level of risk, and compatible with common standards of environmental protection, notably the limitation and optimization of discharges in the environment.

Radiological discharges should be considered in an all-hazard approach. In practice, the radiological impact of discharges should be included in the environmental impact assessment (for new or modified projects) and monitored as necessary under the appropriate regulatory requirements. national requirements established.

4.10 How to apply a GA by operators?

Chapter 3 provides an overview of the identification of practices and workplaces that may involve NORM. The basis of a GA approach by operators is a characterization study and radiological risk assessment. Since reference levels and dose limits are in terms of effective dose, both internal and external exposures should be assessed.

The following are some operational practices that have been shown to be successful.

- Integration of the radiation protection program within the broader operational health, safety, and environmental management plan helps to ensure that the radiation hazards remain in perspective with all other hazards at an operation.
- Consider "collective" control and management actions. For example:
    - area ventilation protects a workgroup, rather than individuals, however, make sure that all work locations are properly ventilated
    - workgroup monitoring rather than individual dosimetry can be done by determining "similar exposure groups"
    - identify general health or safety control that are also effective for radiological hazards
- Ensure that the implementation of controls against the radiological hazard do not degrade the protection against other hazards in the workplace or in neighbouring workplaces.
- Ensure that the personal protective equipment that a worker must wear to protect him/herself against all hazards does not hinder the work to be done, leading to a deterioration of the protection of the worker against some other risks. This is particularly important in the selection of respiratory protection. What protection factor is already required and does the addition of radioactivity to the atmosphere change the choice of equipment (e.g., supplied air or air purifying respirator?)
- An operator should always also ensure that all contractors and service providers are aware of the presence of NORM and the controls that they must follow.
- When assessing doses, consider that this can be done using a graded approach. For example, a high-level screening assessment can be conducted, using conservative assumptions, and if this shows a concern, then a more detailed evaluation can occur using more realistic parameters.

Note that the approach to dose assessment depends upon what needs to be achieved. For example, a screening dose assessment can be used as a starting point to determine compliance or whether a practice can be exempted. A more detailed evaluation is used for higher doses and also helps determine appropriate personal protective equipment. Accurate dose assessment is also good for health assessments and epidemiology.

4.11 Examples of the GA

IAEA Specific Safety Guide SSG-60 [120] addresses the issue of GA in its paragraph 5.7-5.40. Based on the principles of SSG-60, the IAEA developed training materials[16] in the context of the Regulatory Forum for Safety of Uranium Production and NORM (REGSUN). It suggests, for instance, a GA to safety assessment in order to assign the right level of regulatory control. This approach is summarized in the flowchart in Figure 4-2.

[16] https://gnssn.iaea.org/main/REGSUN/MemberArea/LearningWiki/LearningNORM.aspx

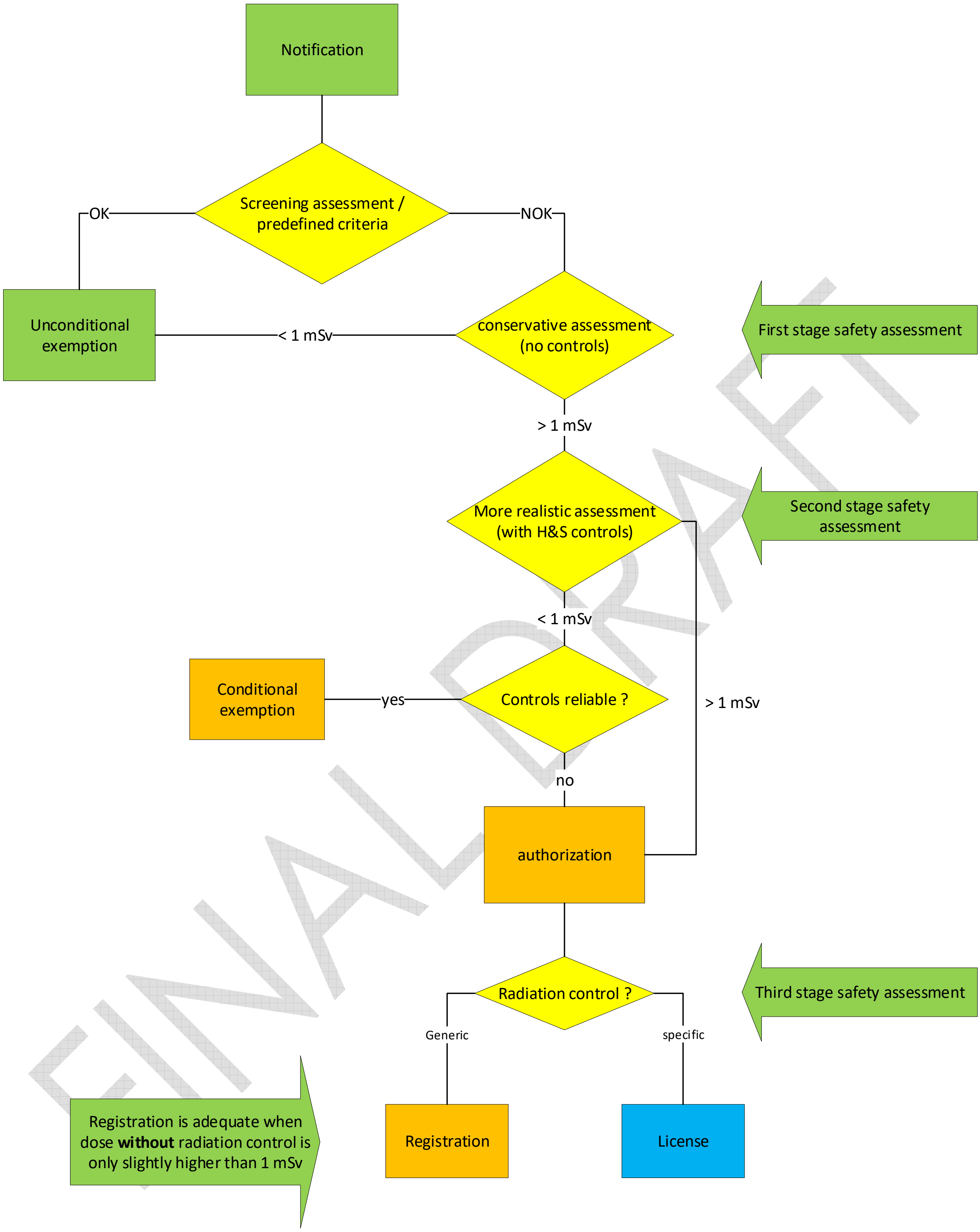

FIGURE 4-2: EXAMPLE OF GA TO SAFETY ASSESSMENT

For each potential requirement in a system of regulatory control, Table 4-1, also developed for training purposes in the context of REGUN, describes possible ways to implement these requirements, taking into account a GA. This table is purely indicative as the effective requirements will depend on national regulations and on the practical case they are applied for.

TABLE 4-1: GA OF REGULATORY REQUIREMENTS – FOR ILLUSTRATION ONLY.

	Notification Only	Registration	Licensed
Management system	not required	simple management system	Full management system covering the require-ments of IAEA GSR Part 2
Procedures	not required	limited set of procedures - not necessarily reviewed by the regulator	Detailed procedures. Reviewed by regulator - including revisions.
Reporting	Only for significant changes (in raw materials or proces-ses). And/or renew-al of notification at a specified frequency	Specific data reported at a specified frequency	extended reporting of activities at a specified frequency
Record Keeping	only to document compliance with notification	required for a limited set of data and procedures	required for an extended set of data.
Training and Education	not required	Basic NORM awareness training	extended training including refreshers training at specified interval
Provision of equipment and facilities	None required	limited set of equipment (PPEs, measurements instruments,…)	extended set - may include engineered facilities such as water treatment plant, barrier, …
Resources – personnel	personnel requested to maintain compliance with notification	personnel with sufficient knowledge of NORM to maintain compliance with regulatory requirements	personnel with radiation protection training responsible for compli-ance with the regulations and with sufficient authority to stop or alter work activities
Resources - financial provisions	Not required	Unlikely to be necessary.	Determination of need for financial provisions should systematically be considered
Worker Dosimetry	Not required	Assessment of compliance through workplace monitoring and simple calculation	Individual dosimetry likely required.
Characterization of Residues	Limited number of measurements. May be based on a screening criteria.	Quantitative analysis necessary. Number of measurements limited to what is necessary to support the dose-assessment.	Quantitative analysis necessary, possibly by certified laboratories. Extensive set of measurements. Detailed sampling protocol to be approved by the regulatory body.

	Notification Only	Registration	Licensed
Environmental monitoring	not required	limited (e.g. random sampling - low frequency)	Detailed monitoring programme with justification of sampling points and parameters; baseline monitoring, if applicable
Safety Assessments	either not required or based on simple, qualitative arguments or preset criteria	screening assessment based on conservative exposure scenarios	detailed assessment
Residue Management Plan	Not required	limited description (e.g. table with categories of residues, quantities, disposal route)	Detailed description including justification of the choice of the disposal route, provisional assessment of quantities to be produced in the future (including from decommissioning), etc.
Clearance & Discharge Limits	residues are beneath preset clearance levels	residues above generic clearance levels but conditional clearance may be considered	residues to be considered as radioactive waste. Licensed discharges.
Posting of Areas	None required	Notice to workers, "Caution Radioactive Material" if applicable	Establish controlled areas
Inspection access	None or may be limited to desk-inspection	Inspections with a limited scope and low frequency	Full scope inspections conducted at periodic frequency.

4.12 Helpful tips

When thinking about the GA and its application, the following are a few tips to keep in mind which are applicable to both regulators and operators.

1. Controls should be proportional to the radiological hazards and risks.
2. Remember that there are other hazards and risks that need to be thought about.
3. The controls for radiation should take into account the controls for the other hazards and risks.
4. Try to be realistic in your considerations – don’t cut corners, but don’t over-protect.
5. Think about how doses could be “optimized” for a specific working activity.
6. Collect data and assess the system applied in regular intervals (according to the risk involved) – and change it, if necessary.

5 CHARACTERIZATION OF NORM

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5.1 Why do we need characterization?

Characterization is fundamental to the management of NORM. Having a clear understanding of the materials, including radionuclide composition, activity levels, host minerals and processes, provides a solid foundation for ensuring good management through evidence and data-based and justifiable decision making. This then provides the necessary information to determine whether the material and particular practices require regulatory control.

This chapter provides an overview of characterization techniques and methods and is a good starting point for commencing and/or thinking about what is good practical practices in the characterization of NORM.

5.2 What information do we need?

A wide range of information is required for proper characterization, which is used for different purposes. Some of these are described below.

- **To estimate doses due to external (gamma or beta) exposure**, we need (highest, mean, or otherwise representative) dose rates at workplaces or other sites where exposure may occur.
- **To estimate doses of internal exposure**, we need information about activity concentrations of the dose-causing long-lived radionuclides U-238, U-234, Th-230, Ra-226, Pb-210, Po-210, Th-232, Ra-228, Th-228; Pa-231, Ac-227. Information on K-40 is not usually required because this radionuclide does not result in a significant additional dose (cf. Chapter 2).
- **To assess whether NORM is exempted** or can be released from control after clearance, we usually must know the activity concentrations of the long-lived radionuclides U-238, U-234, Th-230, Ra-226, Pb-210, Po-210, Th-232, Ra-228, Th-228; Pa-231, Ac-227, and sometimes also K-40. The same holds for transport of bulk amounts of NORM (see Chapter 8).
- **To inform consumers or users** about the radioactivity of products, the activity concentrations of long-lived radionuclides that are most important for RP should be given.
- In some cases, specific information about the exhalation rate of radon (Rn-222, sometimes also Rn-220) from NORM is required. Information about this topic is given in Chapter 2.
- Another particular case is surface contamination, e.g., for categorization of surface contaminated objects (SCO) according to the transport regulations (see Chapter 8). A well-founded categorization of SCO may also require data on long-lived

radionuclides U-238, U-234, Th-230, Ra-226, Pb-210, Po-210, Th-232, Ra-228, Th-228; Pa-231, Ac-227, and K-40.

5.3 How do you obtain the required information?

5.3.1 Where to start?

Industrial facilities are complex structures consisting of many processes, components, vessels, pipelines, reactors, and other units (for example, see a process flow chart in Figure 5-1). It may be challenging to identify the sites where NORM occur.

FIGURE 5-1: VIEW OF A DECOMMISSIONED CHEMICAL PLANT. PHOTO: F. GRANDIA [121]

A good radiation protection practitioner will endeavor to understand the facility in which they work. They will interact with engineers, metallurgists and operational workers to gain an understanding of the processes and mechanisms.

If you must start from scratch, the following steps are recommended:

- Check the feedstock components regarding their radionuclide activities.
- Check the processes that run (or have previously been run) to determine their effect on the radionuclides. Use the basics described in Chapter 2 and the information given in Chapter 3 to identify the relevant units for an investigation.
- Consider that high activity concentrations occur in small amounts of mass.
- Decide on the measurement technique required. In many cases, gamma-dose rates are the most suitable indicator of NORM, but Pb-210 and Po-210 are not detectable by this method.
- Conduct some research on other similar facilities to give you a head start.

Overall, be inquisitive and ask questions. The outcome is that, with a good understanding, you can provide valuable advice that helps protect people and the environment from the potential adverse effects of radioactivity.

5.3.2 Dose rate measurements and other in-situ measurement techniques

In general, there are many ways to measure radiation at NORM. The important cases in practice are described below. It is important to understand the capabilities of the monitoring instrument, including selecting appropriate units, the detector type, detector size, and the integration and response time of the counter unit.

Dose rate measurements

The simplest method for obtaining information about a certain NORM is to measure the ambient dose rate. This can be done with handheld devices that measure gamma radiation levels and provide an overview of the spatial distribution of gamma radiation emitted by the material. When taking measurements, ensure a representative set of results, including high and low levels, but avoid solely focusing on these areas to ensure representativeness.

The values provide a good basis for estimating external doses for workers or members of the public.

When measuring dose from external exposure to radiation, consider the following hints

- Use dose rate meters that are sensitive enough for low dose rates.
- Check the sensitivity by measuring background dose rates. Compare the results with typical value ranges. A value of (40 to 100) nSv/h can be used for a rough estimate (which is largely made up of cosmic radiation and terrestrial radiation).
- One method for understanding the sensitivity of a detector is to measure the dose rate on a lake or other large water body away from the beach (50 m, for example). In such surroundings, the dose rate meter should read about 40 (±10) nSv/h, corresponding to the cosmic radiation dose rate. Note that cosmic radiation is also elevation dependent.)
- Be aware that some radionuclides (such as Pb-210 and Po-210) do not emit detectable gamma dose rates.
- Beware of instruments that read in "counts per second" or "counts per minute". These are not useful for determining dose rates.
- Some dose rate meters can be sensitive to external conditions such as magnetic fields. In these cases, the measurement results are incorrect.

For surveys of dose rates on heaps, large areas of contaminated ground, etc., measurements are usually made at 1 m above ground level. Measurements on smaller volumes, such as drums, big bags, sacks, and other packaging, should be taken at defined distances from the surface. Measurements in contact with, or within 0.1 m of, the surface should consider the geometry and the detector volume when defining the distance for evaluations.

Note 1: This is an example of thinking about monitoring geometry when taking dose rate measurements. In this case, the dose rate measured at 1 m above a ground plane with a radioactive contamination of infinite depth is equivalent to the averaged radiation within a circle with a radius of only a few meters. Measurements at 0.1 m distance represent the radiation from an area with a diameter of a few decimeters. This is due to simple geometry and what the instrument is able to "see" (or more precisely, detect). (Note that the concept of a detector "seeing" radiation is useful when thinking about monitoring geometry. Gamma is highly penetrating, so your detector might be "seeing" radiation from an area that you are not measuring. Keep this concept in mind when in the field.

Note 2: The dose rate from a homogeneous contaminated ground area is related to the activity concentrations of Th-232, U-238 [Ra-226], and K-40 with dose rate coefficients (see Chapter 2). Frequently used are coefficients given in UNSCEAR 2008 [122]):

$$\boldsymbol{H^{*}_{soil}(10)\left(\frac{nSv}{h}\right) = 604 \cdot C_{Th-232}\left(\frac{Bq}{g}\right) + 462 \cdot C_{U-238}\left(\frac{Bq}{g}\right) + 41.7 \cdot C_{K-40}\left(\frac{Bq}{g}\right)} \qquad \text{EQU. 5-1}$$

This formula was checked and confirmed by Hassan et al [123] with highly precise measurements. Note that this is only applicable when secular equilibrium exists (and this is .

Note 3: Measured dose rates include a cosmic-ray component of about 40 nSv/h (at sea level). This component should be considered if Equ. 5-1 is used.

Note 4: Dose rate coefficients for **effective doses** of different age groups and different depths of contamination in soil were published by ICRP [124] and US EPA [125]. A selection of these coefficients is compiled in the Appendix. Note that the coefficients for the effective dose are about 0.7 of the ambient dose rate.

Note 5: Dose rates measured in the spaces between big bags, drums, or parallel stacks can be up to a factor of two higher than the dose rate from a plane (see Section 5.8.1). This is due to geometry and what the instrument "sees".

Note 6: Measurements should take into account the following factors;

- the response time of the instrument, including the size of the detector and whether it is on "fast" or "slow" response
- the directional sensitivity of the instrument
- any unintentional shielding (for example instrument is in a cover or backpack)
- geometry, including any reflecting surfaces.

Contamination monitors

Hand-held contamination monitors are used for determining the presence of fixed or removable radioactive materials on any surfaces, including floors, benches, equipment or in pipes. They also provide an overview of the extent of NORM contaminations on surfaces . Such monitors have sensitive plane detectors usually with areas between 100 cm² and 300 cm².

Pipe probes are a special type of contamination monitor. Such probes can be used to determine the contamination of internal surfaces in pipes.

Unlike dose meters, contamination monitors can be sensitive to alpha, beta, and gamma radiation (depending upon the detector and instrument), so understanding the capability of the instrument is important. These instruments can be used for measuring radionuclides like Pb-210 (via beta-counts) or Po-210 (via alpha-counts).

For measuring NORM contamination, a measuring mode that gives count rates (ips = impulses per second or cps = counts per second) can be used. The ips or cps are corrected to alpha or beta Bq values and then, taking into account the area of the probe, converted into alpha and beta Bq/m², which is a recognized measure of surface contamination. Some instruments allow the measurement of "alpha" cps or "beta-gamma" cps. When measuring beta, the instrument is likely to be cross-sensitive to gamma radiation. This means that the beta measurement might be "seeing" gamma from areas beyond the probe face. Also, due to the range of betas in the air, the instrument may be "seeing" betas from areas outside of the area being immediately measured.

Note 1: To take account of any gamma that might affect beta readings, hold the detector away from the surface (> 1m) and see if it is registering any counts. If so, subtract this from your surface count.

Note 2: Surface contamination probes are very sensitive. You can check the "light seal" of the probe by holding it up to the light. If the detector registers many counts, then you have a light leak, and the probe mylar surface needs repair.

Surfaces with a visible, removable contamination layer should have it cleaned and removed before instrument checking. This could include mud, grease, slurries or other materials. A visual check is usually the first step of a surface contamination check.

Some tips when using the contamination monitor are:

- The main purpose of contamination monitors is to measure very thin radioactive contamination on flat surfaces. When contamination with NORM occurs, several other factors must be considered.
- When there are thicker layers of contamination, the instrument can only be used to indicate if radioactive material is present. Other techniques are required to quantify the radioactivity levels, such as swipe tests.
- Contamination monitors are mechanically sensitive. They can easily be damaged and rendered unusable by mechanical impact. The probe surface is a "light seal", usually a very thin layer of Mylar. This can easily be penetrated by sharp objects such as wire or even small rocks. Any contact of the detector surface with objects must be avoided.
- Because alpha-rays have a range in air of about 5 cm, the detector surface must be placed about 1 cm to 2 cm from the surface of the NORM for measuring alpha-rays. Note also that wet surfaces can attenuate alpha particles, so make sure surfaces are dry or wiped clean.
- Although the detector cannot distinguish between beta- and gamma-rays, beta-rays can be identified by two consecutive measurements: one without shielding and a second by shielding the detector with an aluminum or iron plate with a thickness of about 3 mm. The difference in the results characterizes the beta component.
- In a similar manner, a thick sheet of paper can be used to differentiate alpha and beta measurements.

An example of measurements with a contamination monitor is given in Section 5.8.2.

Portable gamma-spectrometers

In many cases, it is sufficient to measure unspecific quantities like dose rates or pulse rates to obtain a preliminary assessment of larger quantities of NORM. This is almost a screening levels assessment. The exact composition of the materials can then be determined by laboratory analyses.

As described in Chapter 3, the radionuclide composition of NORM in many mining or industrial processes is relatively predictable, and an in-situ measurement of the radionuclide composition may not be necessary. However, there are cases where it may be necessary to differentiate between different NORM types. For example, waste from oil and natural gas extraction is generally dominated by Ra-226 or Ra-228. However, for transport purposes, the Ra-228 decay product, Th-228, is important for determining requirements (cf. Chapter 8), therefore, it may make sense to identify its activity separately. This requires spectrometric measurements. In practice, portable gamma spectrometers with NaI detectors and gamma line resolutions of around 5 % at 1 MeV are usually sufficient for such tasks.

If there is a well-defined measuring geometry, e.g., a plane ground, then a portable gamma-spectrometer can be used for in-situ determination of activity concentrations. However, such determination usually requires calibration via laboratory analyses of samples.

5.3.3 Which methods are suitable for determining activity concentrations of long-lived radionuclides?

For assessing inhalation or ingestion doses, it is necessary to determine the activity concentrations of the long-lived decay-series radionuclides in dusts and ingested materials. The same holds for the characterization of NORM for transport (Chapter 8) or waste categorization (Chapter 7). To do this, it generally requires laboratory-based analyses of the materials. The rows in Table 5-1 show analytical methods that can be used to simultaneously determine radionuclide concentrations. For example, alpha spectrometry can be used to determine concentrations of U-238, U-235, and U-234 simultaneously.

TABLE 5-1: OVERVIEW OF THE GENERAL METHODS FOR THE MEASUREMENT OF LONG-LIVED RADIONUCLIDES

	Radionuclide											
General Method	**Th-232**	**Ra-228**	**Th-228**	**U-238**	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Po-210**	**U-235**	**Pa-231**	**Ac-227**
Alpha spectrometry				✓	✓					✓		
	✓		✓			✓						
							✓					
											✓	
									✓			
ICP-MS				✓	✓					✓		
	✓					✓						
Gamma spectrom.		✓	✓	✓			✓	✓		✓		
Beta-counting		✓						✓				
Emanometry							✓					
Chemical methods	✓											
				✓								

Notes: Alpha spectrometry and beta-counting require radiochemical preparation; Gamma spectrometry partly utilizes gamma-lines of short-lived daughter nuclides; ICP-MS – mass spectrometry; Chemical methods are e.g. fluorimetry, colorimetry; Emanometry means measuring of Rn-222

The most common analytical method, in practice, is **gamma spectrometry** of samples. With this method, the following long-lived radionuclides can be determined in appropriately equipped laboratories using routine procedures:

U-238, Ra-226, Pb-210, Ra-228, Th-228, and K-40.

Determining Th-230, and Ac-227 (via Th-227) by gamma-spectrometry may be possible only if these radionuclides are present at significantly elevated activity levels and there is minimal interference from other radionuclides in the sample. (Hint: check the capability of the laboratory before asking for an assessment).

Generally, solid and liquid samples can be analyzed via gamma spectrometry. To obtain meaningful, reproducible results, samples must be pretreated before measurement. Such pre-treatments may include, for example, screening stones or other coarse parts from the sample, homogenizing the sample by grinding up these coarse parts, and, above all, drying.

Hint: "Drying" is a necessary part of the sample preparation for measurement, even if the regulatory authority requires reporting results for the sample in a state "as released from the workplace".

A good overview of the possibilities and methodical challenges for determining naturally occurring radionuclides by gamma-spectrometry is given in [126]. However, there remain some long-lived radionuclides that cannot or can only be determined by gamma-spectrometry in favorable circumstances. These are

U-234, Th-232, Th-230, Po-210, and Pa-231.

Determining these radionuclides requires specialized methods such as alpha (Po-210) or mass spectrometry (U-234, Th-232), and both of these methods require some chemical pretreatment in a laboratory.

Beta spectrometry by Liquid Scintillation Counting (LSC), measurement of Ra-226 via its gaseous decay product, Rn-222, by emanometry, or chemical determination of uranium or thorium are methods that may be used in special cases.

5.3.4 Which radionuclides can be determined by gamma-spectrometry?

Gamma spectrometry of NORM is challenging. Qualified analyses need experienced laboratory staff. The following facts should be observed [126]:

- The most intensive gamma-lines are usually emitted by short-lived radionuclides. Therefore, gamma spectrometric measurements are frequently based on the detection and evaluation of short-lived decay products. The determination of long-lived radionuclide activities requires that the short-lived radionuclides come into equilibrium with the longer-lived parents. The time for reaching equilibrium is about five half-lives of the decay short-lived radionuclide, and some values are shown in Table 5-2.
- In solid samples, radioactive equilibrium may be frequently assumed (for example, Th-232 in unprocessed geological materials (including coal)). However, liquid samples and organic materials are usually characterized by significant disequilibria. However, such disequilibria may also occur in solid samples obtained from material treatment processes, such as chemical leaching or thermal treatment. Therefore, the origin of any samples should be determined to assess possible disequilibria.

TABLE 5-2: APPROXIMATE EQUILIBRIUM TIMES FOR RADIONUCLIDE ANALYSIS USING SHORT-LIVED GAMMA-EMITTING DECAY PRODUCTS

Radionuclide	Gamma emitters	Time for equilibrium	Crucial radionuclide
Th-232	Bi-212, Tl-208	30 years **(!)**	Ra-228
Ra-228	Ac-228	30 hours	Ac-228
Th-228	Bi-212, Tl-208	20 days	Ra-224
Ra-224	Bi-212, Tl-208	2.5 days	Bi-212
U-238	Th-234, Pa-234m	120 days	Th-234
Ra-226	Bi-214	20 days	Rn-222
Ac-227	Th-227	100 days	Th-227

The following observations are made about the determination and analysis of radionuclides. Many of the observations are based on extensive practical experiences.

- Th-232 has a gamma peak at 63.8 keV with a very low emission intensity of 0.259 %. Because Th-234 has a gamma-peak at 63.3 keV with a higher emission intensity, of 3.75 % Th-232 cannot be determined directly by means of gamma spectrometry in NORM samples. Furthermore, Th-232 cannot be determined by means of the short-lived decay products without independent information about the secular equilibrium in the Th-232-series!
- Ra-228 can be determined by evaluating the gamma peaks of its progeny Ac-228. However, a coincidence summation correction must always be performed [126].
- Th-228 is usually determined by evaluating the gamma peaks of Pb-212 (238.6 keV and 43% emission probability) and Tl-208.
- When considering Tl-208, the branching ratio of 36% at the decay of Bi-212 must be considered. To be sure that an equilibrium actually exists, a sample storage of 3 weeks is required (see Table 5-2). Otherwise, the short-lived radionuclides represent Ra-224.
- U-238 is determined via gamma-lines of its daughters Th-234 ($T_{1/2}$ = 24 d) or Pa-234m. If NORM were processed so that the U/Th-ratio was changed, the secular equilibrium U-238 – Th-234 may be disturbed. In such a case, more than 100 days are required for establishing a new equilibrium.
- Th-230 has a gamma line at 68 keV with a very low emission probability. Usually, it cannot be determined, or can only be determined, in NORM with large uncertainties, but it is possible.
- Ra-226 can be directly determined via its 186 keV gamma line. Because U-235 has a line with nearly the same energy and high emission probability, this is easier when uranium activities are much lower than those of Ra-226 (e.g., in radium scales). Usually, Ra-226 is measured by measuring the Rn-222 progeny Bi-214 and Pb-214. Because Rn-222 may escape from the sample to some extent, a qualified analysis requires storing the sealed sample for about 3 weeks before measurement.
- Pb-210 has a low-energy gamma-line (46 keV). The high background from Compton scattering at such low gamma energies, and the self-attenuation of the low-energy gamma line in the sample, make accurate measurements of Pb-210 difficult [127].
- U-235 emits gammas at 143.8 keV, 163.4 keV, 185.7 keV, and 205.3 keV, but the highest emission intensities at 185.7 keV and 143.8 keV interfere with gamma lines of Ra-226 (186 keV) and Ra-223 (144.2 keV). Because in NORM, the activity of U-235 is about 5% of U-238, a determination of U-235 is usually unnecessary.

- Pa-231 possesses some measurable gamma-lines between 280 keV and 330 keV, but all these lines have emission probabilities of less than 2.5%. Furthermore, as part of the U-235 series, the Pa-231 activity concentrations in minerals are only 5 % compared to U-238 or Ra-226. Therefore, determining Pa-231 by gamma spectrometry is challenging.
- Ac-227 can be preferably determined via its decay product Th-227. The gamma peak that is then preferably evaluated is that of Th-227 at 236.0 keV. Again, as in the case of Pa-231, the activity concentrations are usually low. Because of the high inhalation dose coefficient, this radionuclide needs consideration, particularly if actinium is concentrated by chemical processes.
- K-40 is easily detectable and can be determined via its 1461 keV peak. However, in radium-rich samples such as Ra-scales, a gamma-peak of Ac-228 at 1459 keV must be considered.

These tips are provided as assistance for the practitioner. They are not intended to be absolute but show that thought must be applied when conducting characterization.

1. The most common radionuclides that may be determined by gamma spectrometry are

   Ra-226, Th-228, Ra-228, K-40.

   These radionuclides can be measured using relatively simple detectors, such as Na(I) detectors. In this chapter, the measurement of these radionuclides is referred to as **"basic"**.

2. Using high-resolution gamma spectrometry, as is possible with Ge detectors, for example,

   U-238, Pb-210, and, in favorable circumstances, Th-230 and Ac-227

   can also be determined. This technique is referred to as **"advanced"**.

5.4 What should be considered when taking samples?

Mining and industrial processes are dynamic, with large amounts of material being processed through one or several facilities. Sampling should be taken from moving material streams, only when it is safe to do so, e.g. a conveyor belt or from an intermediate storage site, like heaps, tanks, or silos. The materials can be unpacked or packed in big bags, drums, or containers. A special feature is deposits (scale) in the interior of facility components. Such scales typically occur in facilities for crude oil, natural gas, deep geothermal energy production, sediments in the coal mining industry, deposits of ash in clinker ovens and in coal-fired power plants.

They also occur in the filters in mainly processes and industries including chemical and ore processing industries in pipes, plants, or plant components and also in the combustion of coal, and underground water treatment facilities.

Any sampling strategy should start with clarifying the sampling purpose.

- For determining compliance of large amounts of material with exemption values, averages and "hotspot" sampling is usually sufficient. This also applies to preliminary conservative dose estimation.

- Any assessment based on realistic activity concentrations requires a sampling that is suitable for representing the average concentrations and eventually the statistical distribution (normal, log-normal or other).

Depending on the sampling purpose, the sampling strategy has to be determined and may include:

- Single samples, composite or mixed samples
- Random or systematic sampling (or dose rate measurement)

"Hot-spots" (or "cold-spots") can be identified and purposefully sampled by using mobile dose rate meters. Such purpose-directed sampling should be clearly documented in protocols and strictly taken into account when interpreting measurement results.

Sampling should be representative and based on a defined and statistical sampling plan. This plan should also take into account the material's origin. This can provide an insight into the radioactive properties (see Chapter 3). Also, check to see if other information is available on any treatment of the material. This can also provide useful information.

When preparing the sampling plan, the material types and their specific requirements must be considered. An overview of material types and their sampling characteristics is compiled in Table 5-3. Also consider any potential hazards from the material when handling (for example, an acidic solution).

TABLE 5-3: MATERIAL TYPES AND THEIR SAMPLING CHARACTERISTICS

Type	Sampling characteristics
Dust	Very fine-grained. Normally homogeneous. Easy to sample.
Sludge	Very fine-grained. Sampling execution is easy (if the sludge is accessible). Note: Stratification due to gravitational settling may result in some inhomogeneity! Moisture or oil content must be taken into account.
Gravel, sand, or other granular material	Moderate grain size. Sampling execution is easy.
Rocks, fragments, and other lumpy material, e.g., demolition waste or unbroken slag	Large grain size. Sampling execution may require shredding. Assessment of representativity needs additional information (e.g., dose rates)
Deposits (Scales)	Difficult to sample due to limited accessibility. Practical obtainable sample masses are usually small. Assessment of representativity needs additional information (e.g., dose rates)
Operating materials (waste with collected cleaning rags, gloves, etc.	Highly inhomogeneous in terms of both material and specific activity. Assessment of representativity needs additional information (e.g., dose rates)

The sampling plan should at least include:

- Necessary sampling equipment. Note: bulk amounts have three dimensions. It may also be necessary to take samples from deeper layers.

- Accessibility of the sampling site and non-radiological hazards. When sampling is required for bulk material, the first step is to ensure it is undertaken safely. Bulk materials can move, resulting in engulfment or entrapment.
- Necessary safety equipment.
- Requirements of the laboratory regarding sample size. For representative samples the grain size of the material must be considered.
- Preparation of sampling protocols and reports.
- Clear labeling of sample with ID, location of sampling, date of sampling, and person talking sample.
- Avoid cross-contamination by using different sampling tools for higher radioactive samples and background samples.

5.5 Measurement uncertainty, and how can the uncertainties be reduced?

Uncertainty is always important in sampling programs. The following gives some elemental basics.

When using gamma-spectrometry (analog relations hold for alpha-spectrometry), a sample with mass m is analyzed by registering the total number of signals (impulses, counts) N in a detector attributed to a gamma-energy E emitted by radionuclide r. The (total) activity A_r of radionuclide r in the sample is calculated by

$$\boldsymbol{A_r} = \frac{\boldsymbol{N(E_r) - N_{BG}(E_r)}}{\boldsymbol{p(E_r) \cdot \epsilon(E_r) \cdot G}}$$ *EQUATION 5-1*

where

- $N(E_r)$ is the total number of counts at gamma energy E registered in the measuring time t caused by radionuclide r
- $N_{BG}(E_r)$ is the number of background counts at gamma energy E_r in the measuring time t
- $p(E_r)$ is the gamma-ray emission probability of the gamma-emitter "r" at energy E (number of gamma particles emitted per Bq)
- $\varepsilon(E_r)$ is the counting efficiency of the detector at energy E_r (part of the registered gamma particles per total number of gamma particles that reach the detector)
- G is the geometry factor, i.e., the part of the total emitted gamma particles that reach the detector.

The activity concentration is calculated by

$$\boldsymbol{C_r} = \frac{\boldsymbol{A_r}}{\boldsymbol{m}}$$ *EQUATION 5-2*

With m – sample mass.

Since the decay process is random (stochastic), the accuracy of a radiometric measurement is determined by the number of observed events N (see Box 5-1). Because the number of counts depends on the total activity of the sample, larger samples yield better counting statistics. However, the total volume of a sample is limited by the capacity of the measuring device. For gamma-spectrometry, sample volumes of 0.5 – 1 liter are feasible. Very small samples, e.g., 10 g, require a 50-100-fold higher activity concentration to achieve the same count rate.

BOX 5-1: ELEMENTAL STATISTICS

According to Poisson statistics, the relative standard deviation ΔN with N registered counts is

$$\frac{\Delta N}{N} = \sqrt{\frac{1}{N}}$$

For the count rate, Z = N / t follows

$$\frac{\Delta Z}{Z} = \sqrt{\frac{1}{Z \cdot t}}$$

→ The statistical measurement error is smaller the longer the measurement time and the higher the sample count rate.
→ Measurements of very low activity require very long measurement times.
→ Larger sample masses allow lower statistical measurement uncertainties.

For reporting the measurement uncertainties, the following three terms are used:

- **Decision limits** are defined as the value at which (in a statistical test) the hypothesis that the measurement result represents a null effect is rejected with the statistical probability of error (e.g., 5 %).
- **Detection limits** are defined as the smallest (true) value of a measurand for which, if the detection limit is exceeded, the probability of regarding this measurement as a zero effect (error of the second kind) is equal (e.g., 5 %). If the error probabilities are small, detection limits are always larger than recognition limits!
- **Confidence limits** are values that define a range that contains the true value of the measurand with a probability (e.g., 67 % = 1; 95 % = 2) [128].

Decision limits are used to compare measurement methods, whereas detection limits are used to assess individual results.

5.6 How do we get data on the complete set of decay series radionuclides?

This section provides methods for considering the characterization of NORM when incomplete sets of data exist. While the methods are not exactly qualitative, they are useful for initial screening or preliminary assessment to determine whether further analysis is necessary.

5.6.1 The indirect determination approach

As described in Section 5.2, the knowledge of the complete set of long-lived decay series radionuclides is important for many reasons. However, as shown in Section 5.3.3, such a complete set of radionuclides cannot be determined with the commonly used method gamma-spectrometry.

To speed up assessments, manage costs, and to avoid additional analyses, a practical approach is needed to obtain information on other radionuclides in the decay series with only a limited set of measured radionuclides. Such an approach can be an **indirect** determination of decay-series nuclides based on knowledge of the radionuclide compositions

From a practical perspective, the following questions are relevant.

- What type of NORM can be sufficiently characterized based only on a basic determination of Ra-226, Ra-228, and Th-228 only? (Sufficient for dose calculation, classification, etc.)
- What type of NORM can be sufficiently characterized by advanced, high-resolution gamma-spectrometry?
- What type of NORM cannot be sufficiently characterized by gamma-spectrometry? (and therefore, require more detailed analysis)

To answer these questions, an understanding of the radiological characteristics of the material is necessary for all radionuclides with half-lives longer than 100 days. These radionuclides are:

Th-232, Ra-228, Th-228, U-238, U-234, Th-230, Ra-226, Pb-210, Po-210, [U-235], Pa-231, Ac-227.

Because the ratio of U-235 to U-238 is well known, it can be omitted from direct characterization. However, Pa-231 and Ac-227 concentrations are important in certain cases and are therefore included in the following descriptions.

As described in Chapter 3, the composition of the radionuclides in a specific NORM comes directly from the chemical and physical processes that led to its formation. The typical nuclide patterns (and radionuclide ratios) described in Chapter 3, together with the basic knowledge of their physical and chemical behavior from Chapter 2, can be used to estimate the activity concentrations of radionuclides missing in gamma spectrometry.

Suppose we have measured the activity concentration C_{r1} of radionuclide r1 (e.g., Ra-226) and can estimate from our general knowledge of the radionuclide composition, the normalized activity concentration ratio of a not (easily) measurable radionuclide r2 (e.g., Th-230) related to r1, i.e. $\frac{C_{r2N}}{C_{r1N}}$, then C_{r2} can be calculated by

$$\boldsymbol{C_{r2} = C_{r1} \cdot \frac{C_{r2N}}{C_{r1N}}} \qquad \text{EQUATION 5-3}$$

This kind of determination can be referred to as "**indirect determination**".

The following rules should be applied for indirect determination:

1. Any indirect determination should be based on a radionuclide composition that takes into account the physics and chemistry of the chemical elements of NOR within the processes.
2. Radionuclide compositions, as shown in Chapter 3, can be used as a reference but **should be adapted on a case-by-case basis**. Examples of how to make this are given below.
3. In any case of uncertainties, a conservative approach should be used, i.e., the activity concentration of the missing radionuclides should be assumed to be in equilibrium with the maximum measured activity concentration for the specific U-238 or Th-232 series.
4. The indirect determination is not suitable for NORM with Po-210 as the dominant radionuclide (e.g., Figure 3-18, Pre-treatment processes).

For uranium, the activity concentrations of U-234 and U-238 can be assumed to be the same, except in water treatment residues, where U-234 may be in excess of U-238. Additionally, the natural activity ratio C(U-235)/C(U-238) is the same in all NORM and is approximately 0.05. (Note that the mass ratio is 0.007, and this is due to the different half-lives.) U-235 has a relatively low dose effect and, in practice, can be generally disregarded in NORM from a radiation protection point of view.

For all other chemically identical radionuclides, in particular Th-232 and Th-230, ratios cannot be determined without a proper radionuclide analysis.

The rest of this chapter provides specific NORM examples. The radionuclide concentrations of the measured radionuclides have been normalized, and other radionuclide concentration values have been estimated based on the type of NORM. Note that these are examples only, but do provide information for a first assessment.

In the graphs in the following example, the normalized radionuclide concentrations have been assessed by the following methods (included in the legends to the graphs).

a. **Direct (basic)** – based solely on simple gamma spectroscopy (NaI) measurement of Ra-226, Ra-228, Th-228
b. **Indirect (basic)** – based on simple gamma spectroscopy together with the practitioner´s knowledge of the "type" of NORM,
c. **Direct (advanced)** – based on advanced gamma spectroscopy (e.g., Ge-detectors) and including additional radionuclides being U-238, Pb-210 (and sometimes Th-230 and Ac-227),
d. **Indirect (advanced)** – based on advanced gamma spectroscopy together with the practitioner's knowledge of the "type" of NORM.

These examples are indicative and provide the practitioner with a "starting point" for assessing NORM across different industries or origins.

5.6.2 Examples for indirect determinations

Example 1: Ores and minerals

NOR in minerals and ores of geological ages are generally accepted to be in a secular equilibrium. Therefore, for characterization, the determination of one radionuclide of the U-238 and Th-232 series is sufficient. These radionuclides can be Ra-226 and Ra-228/Th-228 (in the literature frequently named "Th-232"), determined by gamma spectrometry or chemically analyzed U (as proxy for U-238) and Th (for Th-232).

Two examples that shall help in understanding the indirect determination are given in Figure 5-2 The diagrams in this figure show the relative radionuclide concentrations of two different ore or mineral samples. Note that the legend refers to the methods outlined directly above. Note also that the total activity concentration is normalized to 1 – for example, in the first ore sample below, the U-238 series contributes 80% of the activity concentration, and the Th-232 series contributes 20% of the activity concentration.

All materials of this type are characterized by decay series in a radioactive equilibrium. The activity of the missing radionuclides can easily be added because a secular equilibrium can be assumed in the U-238 or Th-232 series. Radionuclides of the U-235 series can be added with 5 % of the activity concentration of the U-238 series.

The information gained by a "direct (basic)" characterization is sufficient for a complete characterization of such a type of NORM.

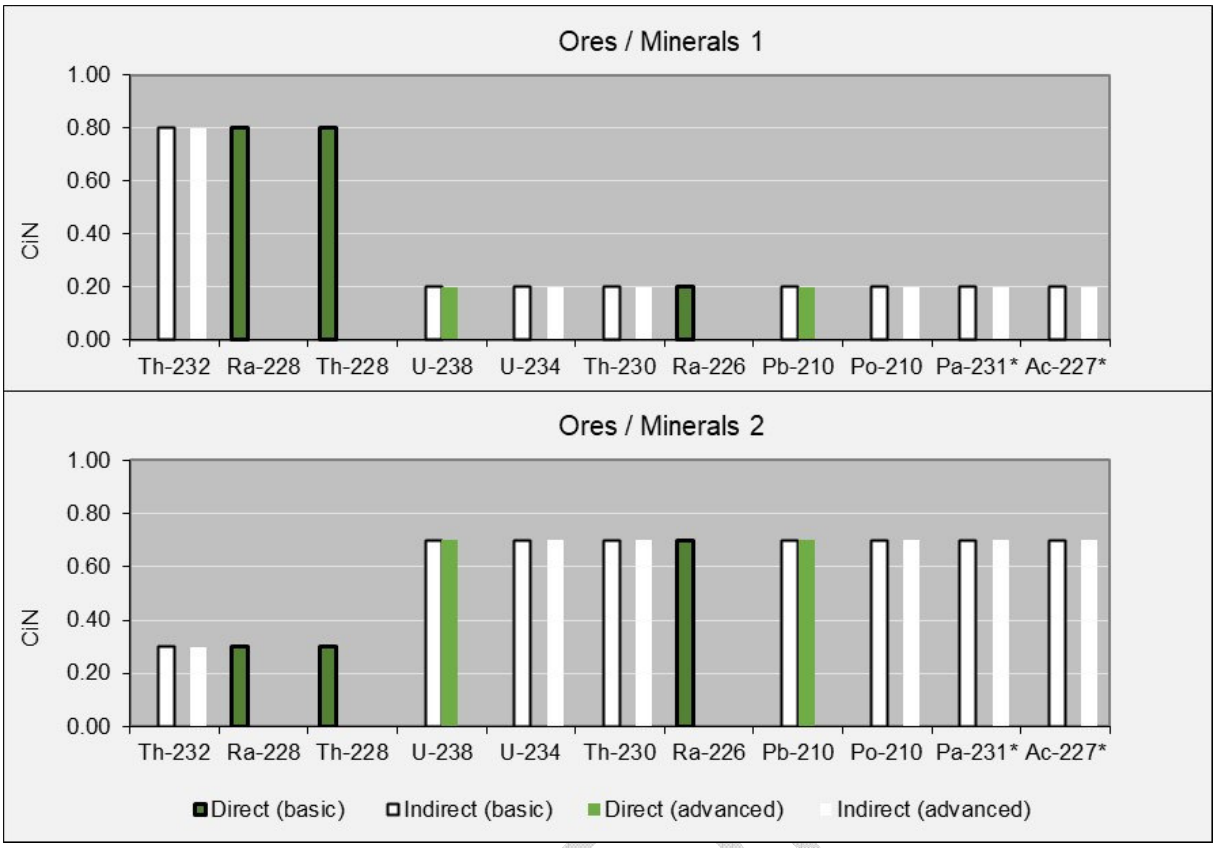


FIGURE 5-2: DIRECT AND INDIRECT DETERMINATION OF NUCLIDE COMPOSITIONS OF ORES OR MINERALS

Practical example:

In a bauxite sample, you have determined by simple gamma-spectrometry:

Ra-226: 0.35 Bq/g; Ra-228: 0.21 Bq/g; Th-228 0.25 Bq/g

Based on the data, you can infer:

U-238 = U-234 = Th-230 = Pb-210 = Po-210 = 0.35 Bq/g; (Pa-231 = Ac-227 = 0.018 Bq/g)

Th-232 = 0.5 × (0.21 + 0.25) Bq/g = 0.23 Bq/g

Your reasoning: Bauxite is an ore of geological age. The decay series must be in equilibrium.
Your assessment: The results obtained by basic gamma spec plus indirect determination are a sound basis for dose estimations and further radiation protection planning.

Example 2: Solid leaching residues

This example refers to the digestion of ores or ore concentrates, which is a central process in hydrometallurgy. In practice, there is a wide variety of procedures. Alkalis or acids are used for digestion. A widely used leaching agent is sulfuric acid. As shown in Chapter 2, leaching with sulfuric acid mobilized uranium and thorium (and actinium). Radium and lead remain in solid residues.

Referring to the examples described in Chapter 3, two examples are depicted in Figure 5-3 and show the relative radionuclide concentrations. The first approach depicted in the diagram is for an unnamed "metal ore" and the second is for titanium dioxide.

A characterization of leaching residues based only on Ra-226, Ra-228, and Th-228 ("direct (basics)") provides an incomplete picture of the real radionuclide composition. Therefore, indirect determination needs independent information on activity ratios.

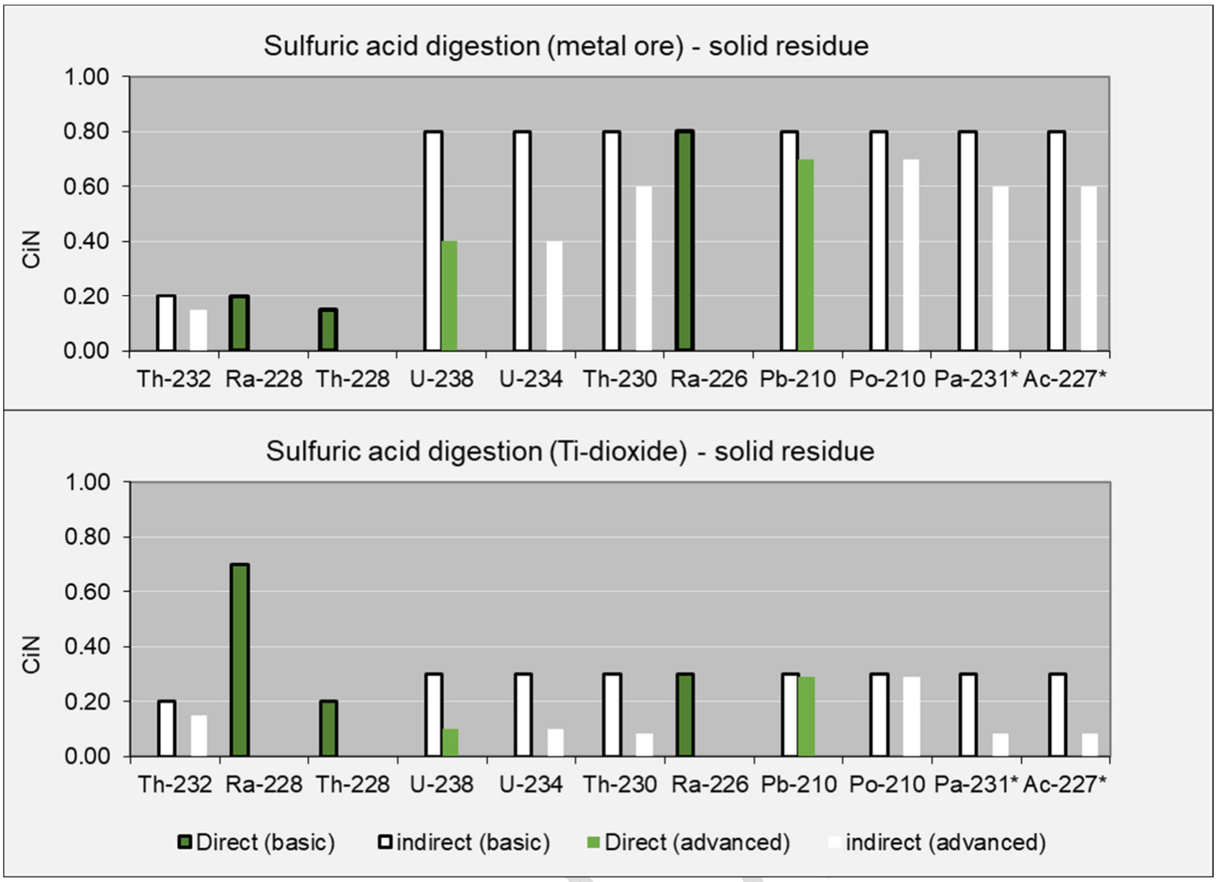


FIGURE 5-3: DIRECT AND INDIRECT DETERMINATION OF NUCLIDE COMPOSITIONS OF DIGESTION RESIDUES

For example, if U-238 (via Th-234) and Pb-210 have been measured ("direct (advanced)"), U-234 and Po-210 can be indirectly determined by assuming an equilibrium with their reference nuclides U-238 (for U-234) and Pb-210 (for Po-210). In addition, based on the composition patterns in Figure 3-7, Th-230 can be assumed to be in equilibrium with U-238 or estimated as the average of U-238 and Ra-226.

Because the Pa-231 and Ac-227 values are ratioed with Th-230, the actual values can be obtained by dividing the Th-230 concentration by 20.

Practical example:

Basic gamma spectrometry of a sulfuric acid digestion residue of ilmenite gave:
Ra-226: 0.23 Bq/g; Ra-228: 0.91 Bq/g; Th-228 0.45 Bq/g
Based on these data and knowing the typical composition of sulfuric acid residues, you can infer:
U-238 = U-234 = 0.23 Bq/g; Th-230 = (0.45/0.91) × 0.23 Bq/g = 0.11 Bq/g;
Pb-210 = Po-210 = 0.35 Bq/g; (Pa-231 = Ac-227 = 0.05 ×0.23 Bq/g = 0.012 Bq/g)
Th-232 = 0.45 Bq/g
<u>Your reasoning</u>: In sulfuric acid residues, radium isotopes have the least leaching effect. The activity concentrations of all other radionuclides may be lower, but without direct determination, a conservative assumption must be applied.
<u>Your assessment</u>**:** The results obtained by basic gamma spec plus indirect determination are a reasonable conservative approximation for dose estimations and further radiation protection planning. Advanced gamma spectrometry will show that U-238 has lower concentrations, and Pb-210 is similar to Ra-226. This will allow a better estimation of doses.

Example 3: Precipitated sulfates

Precipitated sulfates are typical NORM residues found in oil and gas production and in many hydrometallurgical processes. They can be generated when lime is added to a sulfuric acid leachate for removing undesired elements. Examples described in Chapter 3 include phosphogypsum and titanium dioxide production. Similar processes occur in some rare-earth processing. Other sulfates are produced as precipitates from brines, and also as hard scales in oil and gas production.

In acid leachate solutions, uranium and thorium (as well as Ac-227 and Pa-231) usually dissolve and can occur in significant concentrations. These radionuclides are also present in brines only at very low concentrations, frequently below detection limits.

These relationships must be considered when considering the "indirect" method of determining radionuclides.

In Figure 5-4, the direct and indirect determination of the nuclide composition for the two examples described above is shown.

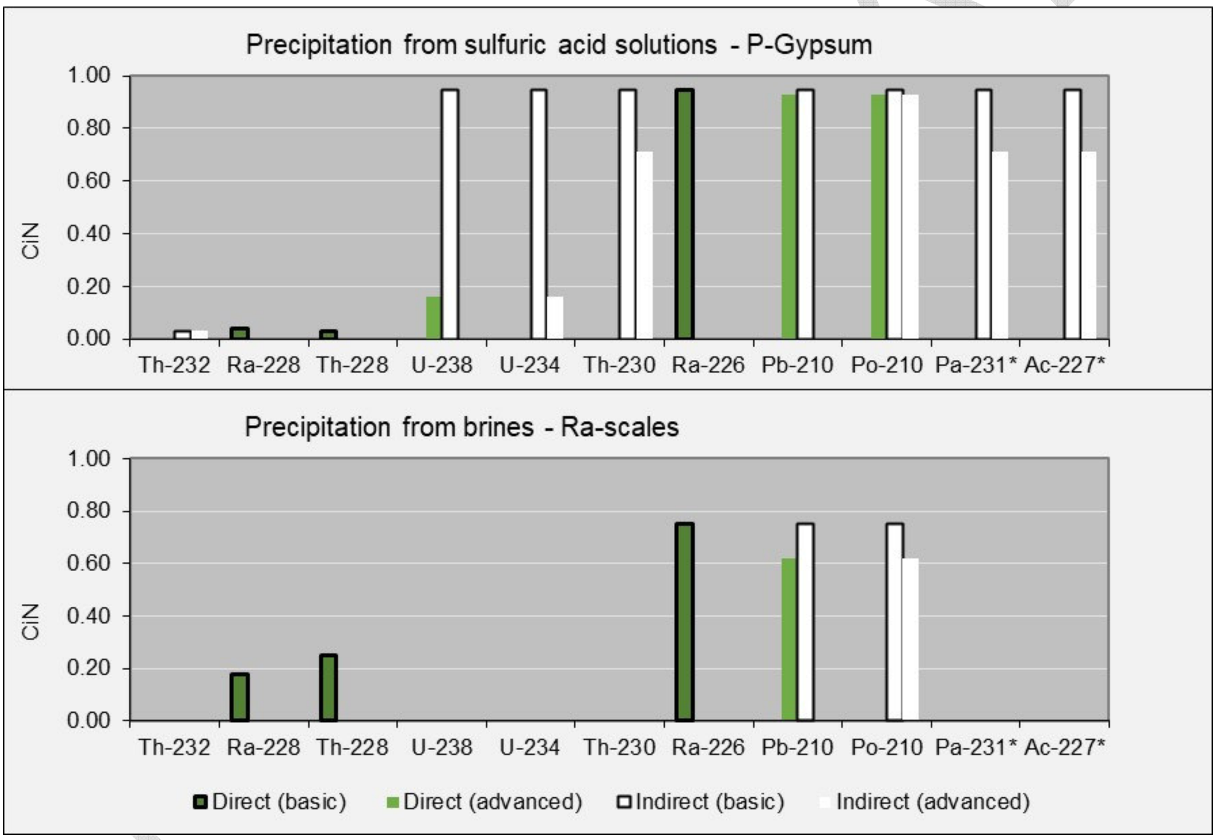


FIGURE 5-4: DIRECT AND INDIRECT DETERMINATION OF NUCLIDE COMPOSITIONS OF PRECIPITATED SULPHATES

In the case of technical precipitation from a sulfuric acid solution, the radionuclides to be determined indirectly should be conservatively transferred from the directly measured activities. (Hint: As shown in Chapter 8, Th-230 (and Ac-227) have a considerable influence on the hazardous goods classification for transportation, so you may need to use more advanced analytics if the material is to be transported.)

U-238, U-234, Th-232, and Th-230 (as well as Pa-231 and Ac-227) can usually be disregarded in the precipitates from produced waters. However, a basic measurement of only Ra-226, Ra-

228, and Th-228 is not sufficient for characterizing deposits in facilities from natural gas or geothermal production because such deposits may be dominated by Pb-210.

Practical example:

Basic gamma spectrometry of a scale sample from a geothermal facility that is operating with hot brines gave:

Ra-226: 23 Bq/g; Ra-228: 9.1 Bq/g; Th-228 4.5 Bq/g

Based on these data and knowing the typical composition of scale from brines, you can infer:

U-238 = U-234 = Th-230 = negligible (=0); Pb-210 = Po-210 = 23 Bq/g;
(Pa-231 = Ac-227 = negligible)
Th-232 = negligible

Your reasoning**:** In hot brines, radium concentrations are high, and radium isotopes are accumulated in precipitated barium sulfates. Uranium and thorium are contained in the hot brines with very low activity concentrations. Only Pb-210 may occur at higher activity concentrations; without direct determination, assuming equilibrium Pb-210 = Po-210 = Ra-226 is a practical estimate.

Your assessment**:** The results obtained by basic gamma spec plus indirect determination are sufficient for dose estimations and further radiation protection planning if Pb-210 does not strongly dominate.

Advanced gamma spectrometry will provide a better basis for Pb-210. Because (in the example!) Th-228 is much lower than Ra-228; the scales are "young", and consequently, Pb-210 is probably much lower than Ra-226.

Example 4: Slags, ashes

Smelting and other high-temperature treatments are common within industry, with processes differing in temperatures and additives (see Chapter 3).

Data from iron slag and copper smelting slag demonstrate radioactive equilibria except for Pb-210 (with Po-210), which volatilizes above about 800°C. Electric-furnace processes operating at temperatures above 2000°C may also result in significant radium evaporation, thereby reducing activity concentrations associated with precursor nuclides. The important point is that radionuclides can report to final products, slags, and residue streams or in gas handling systems.

In Figure 5-5, the direct and indirect determination of the nuclide composition for the two examples described above is shown.

Basic gamma-spectrometry is sufficient to characterize slag. The reduced Pb-210 (and Po-210) activity is frequently of minor importance for dose assessments. Assuming equilibrium Pb-210 (Po-210) with Ra-226 is a conservative approach from a radiation protection perspective. However, do not forget to supplement Th-230 and Th-232 for inhalation dose estimations!

In the case of fused minerals, radium may be evaporated and consequently reduced related to Th-232 and U-238 (U-234). A characterization based on Ra-226, Ra-228, and Th-228 ("basic") is not sufficient. It may underestimate actual activity concentrations of Th-232 and U-238 (U-234, Th-230). Therefore, the advanced gamma-spectrometry and, in cases where Th-232 is important, an alpha-spectrometry may be required. However, such more sophisticated methods can be limited to determining a typical (normalized) nuclide vector. If such a nuclide vector is sufficiently defined for practical purposes, simple gamma spectrometry ("basic") may be sufficient for complete characterization.

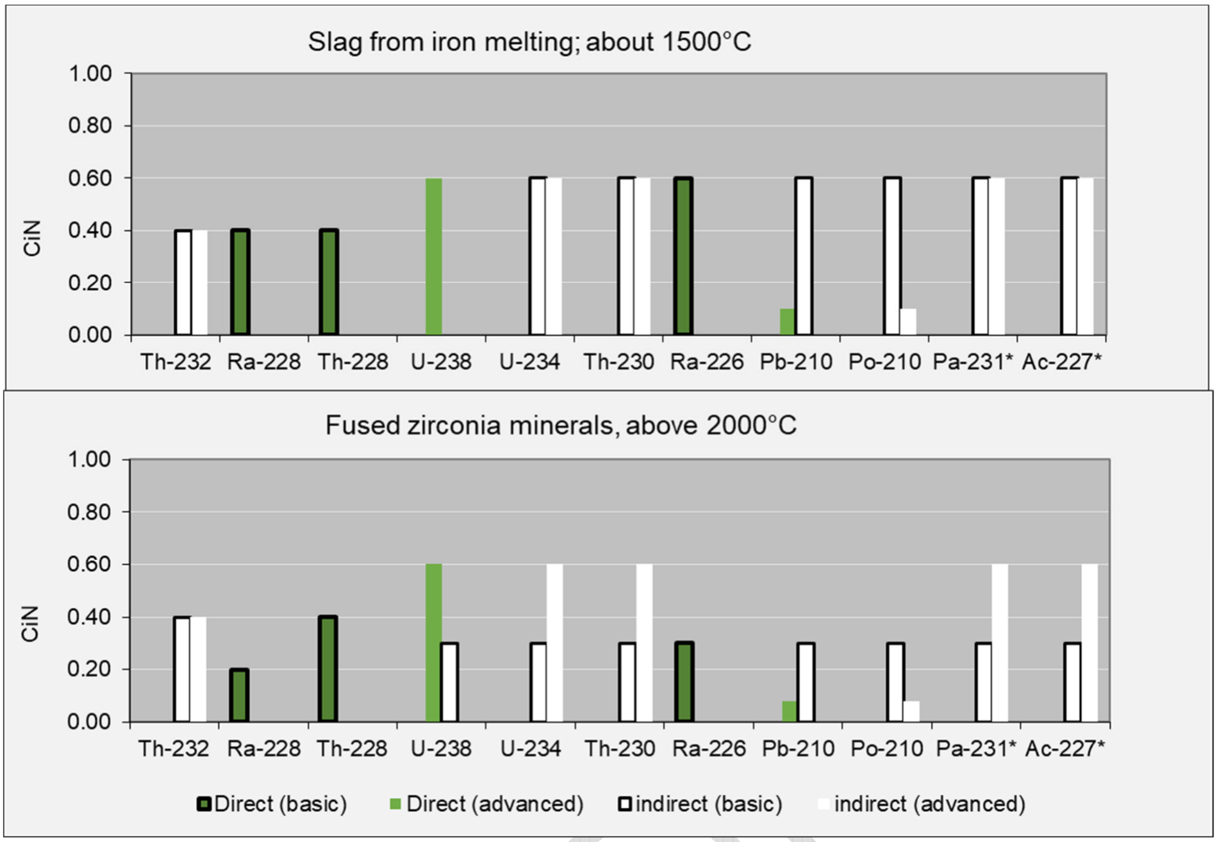


FIGURE 5-5: DIRECT AND INDIRECT DETERMINATION OF NUCLIDE COMPOSITIONS OF SLAGS AND FUSED MINERALS

Bottom ashes from coal-fired power plants usually show nearly activity equilibria in the Th-232 and U-238 series. Therefore, a basic gamma-spectrometry plus indirect detection of the other radionuclides is usually sufficient for complete characterization.

Fly ash from coal-fired power plants may be slightly enriched in Pb-210 (Po-210). However, the effect is less pronounced than in metallurgical filter dust. Fly ashes from wood-fired facilities in the northern hemisphere may contain Cs-137 in activity concentrations exceeding 1 Bq/g.

Hint: Because in recent biological materials, the decay series are not in equilibrium, ashes from wood firing require at least advanced gamma spectrometry as a basis for characterization.

Practical example:

Basic gamma spectrometry of a sintered zirconia brick (AZS) gave:
Ra-226: 3.3 Bq/g; Ra-228: 0.9 Bq/g; Th-228 1.0 Bq/g
Based on these data and knowing the typical composition of sintered zirconia , you can infer:
U-238 = U-234 = Th-230 = 3.3 Bq/g; Pb-210 = Po-210 = 3.3 Bq/g
Th-232 = 0.95 Bq/g
Your reasoning: In sintered zirconia, a radioactive equilibrium with exception of Pb-210, Po-210 can be assumed. Setting Pb-210 = Po-210 = Ra-226 is a conservative approach because Pb-210 may be significantly reduced.
Your assessment: The results obtained by basic gamma spec plus indirect determination are conservative regarding dose estimations and further radiation protection planning. Advanced gamma spectrometry will provide a better basis for Pb-210.

Example 5: Dust from high-temperature processes

Pb-210 or Po-210 are the radionuclides with the highest activity concentrations in filter dust and fly-ash from high-temperature processes. Therefore, advanced gamma-spectrometry is necessary for the characterization of such types of materials.

Two examples of indirectly supplemented nuclide compositions of filter dust from high-temperature processes are shown in Figure 5-6.

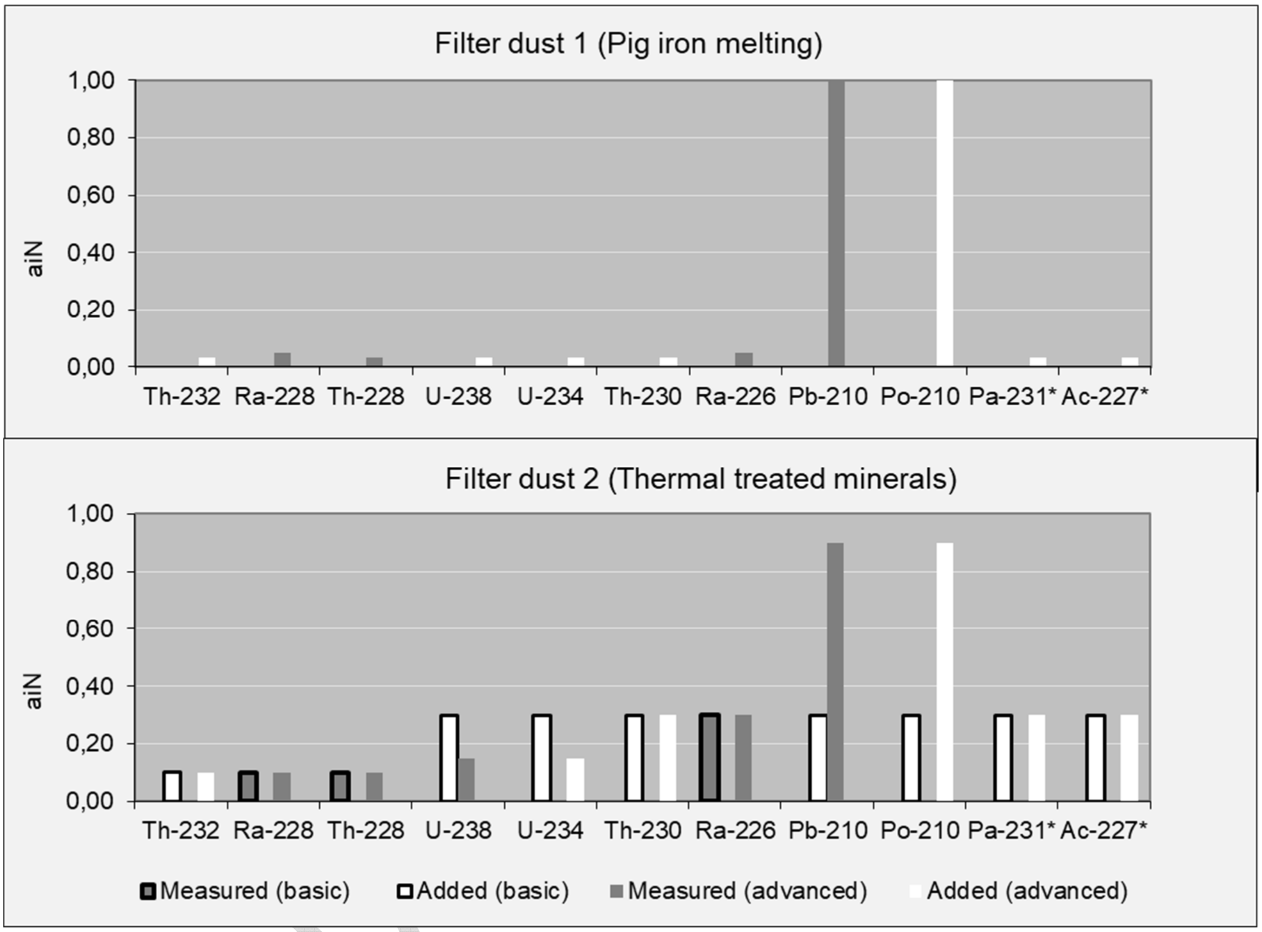


FIGURE 5-6: EXAMPLES OF INDIRECTLY SUPPLEMENTED NUCLIDE COMPOSITIONS OF FILTER DUST FROM HIGH-TEMPERATURE PROCESSES

In metallurgical processes such as pig-iron melting (example 1), the long-living precursors of Pb-210 occur at very low activity concentrations. Dust from melting minerals (such as zirconia) in electric furnaces at temperatures above 2000°C (e.g., example 2) may be enriched in radium, i.e., the activity ratios Ra-228/Th-232 and Ra-226/U-238 are >1. Advanced gamma-spectrometry is necessary for realistic characterization in such cases.

A critical radionuclide in such materials is Po-210. From a practitioner's point of view, an equilibrium Po-210–Pb-210 can be assumed when process temperatures exceed 1200°C. At lower temperatures, Po-210 may dominate significantly. Alpha-spectrometry of Po-210 is required to characterize such dust materials; however, gross alpha counting can be used to provide an indication.

Dust enriched in Po-210/Pb-210 may be present in clinker ovens.

Practical example:

Basic gamma spectrometry of a blast furnace dust gave:
Ra-226: <0.1 Bq/g; Ra-228: < 0.1 Bq/g; Th-228: < 0.07 Bq/g
Based on these data and knowing the typical composition blast furnace dust, you must state:
The measured results are <u>not sufficient</u> to assess the radioactivity of the blast furnace dust.
<u>Your reasoning</u>: In blast furnace dust Pb-210 and Po-210 may be significantly enriched.
<u>Your assessment</u>: The results obtained by basic gamma spec plus are not sufficient for dose estimations and further radiation protection planning.
Advanced gamma spectrometry is necessary for Pb-210 determination.

Example 6: Thoriated products

Of the naturally occurring radionuclides, only uranium and thorium are used for technical purposes other than those related to ionizing radiation. While pure natural uranium has a very simple nuclide composition and can, therefore, be characterized radiologically using simple means, the composition of chemically separated thorium is more complex. On the one hand, a proportion of Th-230 is always present, and on the other, the decay products' composition changes over 20 years after chemical separation from ores.

Two examples of how thorium can be characterized are shown in Figure 5-7.

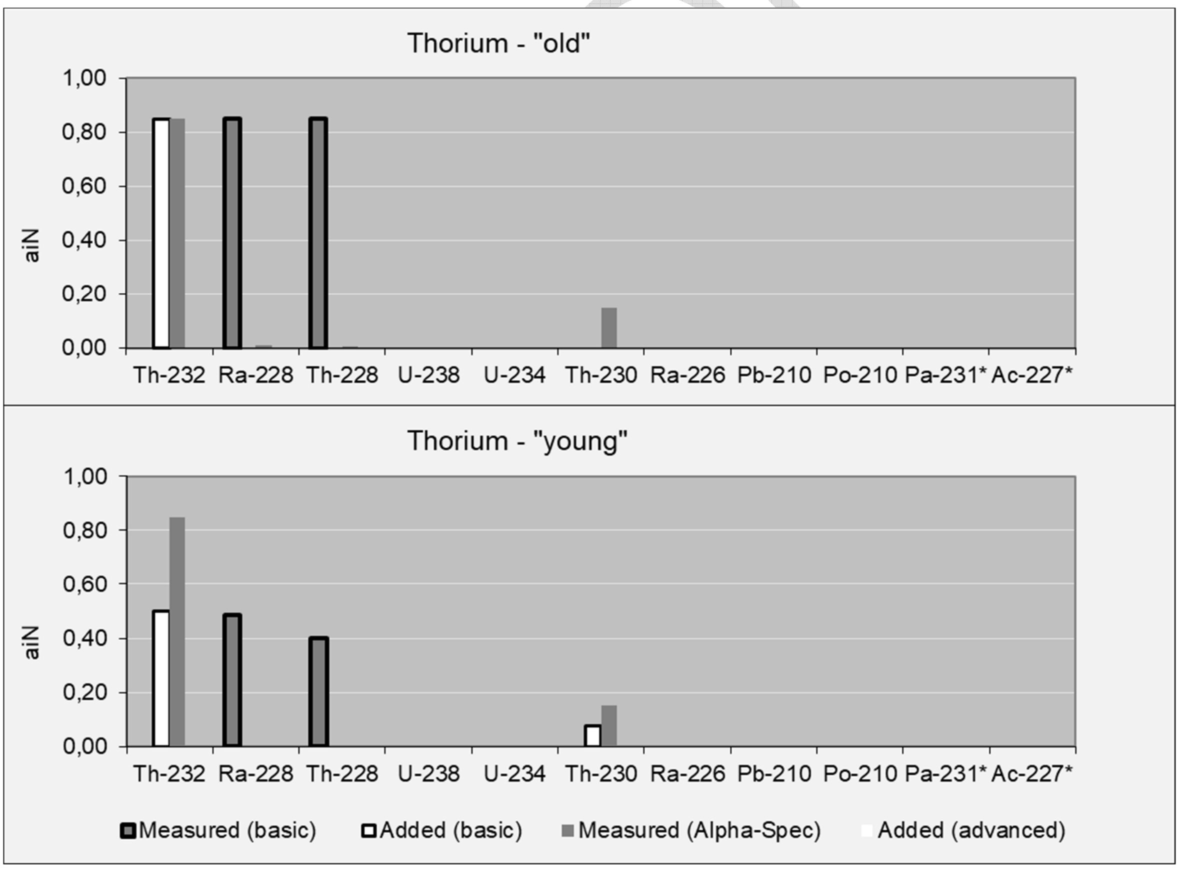


FIGURE 5-7: NUCLIDE COMPOSITION OF CHEMICALLY PURE THORIUM COMPOUNDS

Because the nuclide composition of the Th-232 series consists only of Th-232, Ra-228+, and Th-228+, the missing Th-232 can be indirectly determined based on gamma-spectrometry of Ra-

228 (Ac-228) and Th-228 (Pb-212, Tl-208) if the material is actually "old". The other "missing" radionuclide in thoriated materials is Th-230. An exact determination of Th-230 requires alpha-spectrometry. For a rough estimate, an activity concentration ratio of Th-230/Th-232 between 0.1 and 0.2 (10% - 20%) has been found to be applicable.

Freshly separated thorium consists of Th-232 and Th-228 in activity equilibrium, plus a (small) part of Th-230. Because Th-228 decays much faster than Ra-228 ingrowth, the activity concentrations of gamma-active radionuclides Ra-228 and Th-228 are significantly lower than that of Th-232 for a period of about 10 years. After about 5 years, Ra-228 and Th-228 have nearly the same activity concentration (Figure 5-8). If this stage is interpreted as a secular equilibrium, the activity of Th-232 is underestimated by a factor of 2!

The temporal changes in the normalized radionuclide composition and the activity ratio Ra-228/Th-228, which is useful for assessing the age of thorium, are shown in Figure 5-8.

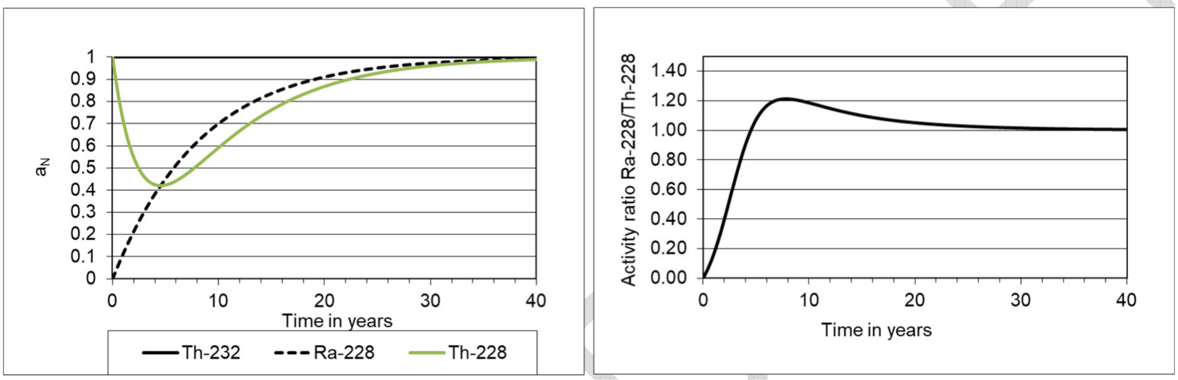


FIGURE 5-8: TEMPORAL PROGRESSION OF THE NORMALIZED ACTIVITY CONCENTRATIONS IN THORIUM (LEFT) AND OF THE ACTIVITY RATIO RA-228/TH-228 (RIGHT)

Practical example:

Basic gamma spectrometry of a thoriated welding rod gave:

Ra-226: below detection limit; Ra-228: (19±2) Bq/g; Th-228: (17±1) Bq/g

Based on these data and knowing the behavior of thorium decay products in chemically separated thorium, you can infer:

U-238; U-234; Pb-210; Po-210 = negligible; (same for Pa-231, Ac-227)

Th-232 = 36 Bq/g (1 % ThO_2)

Your reasoning: In thoriated welding rods, a radioactive disequilibrium can occur. Assuming such a disequilibrium the activity ratio Ra-228/Th-228 = 1.12. Consequently, the Th-age in the welding rod is between 6 and 15 years. With 6 years Th-232 is about 2 x Ra-228 = 38 Bq/g. With 15 years Th-232 is about 1.2 Ra-228 = 23 Bq/g. The first result is close to 36 Bq/g, the typical Th-232 activity concentration in WT10 (1 % ThO_2) rods. Therefore, and because the result is conservative from a radiation protection perspective, 36 Bq/g are applied.

Your assessment: The results obtained by basic gamma spec plus indirect determination are sufficient for characterizing the welding rods and the further radiation protection planning. Advanced gamma spectrometry could eventually provide a better basis for Th-230. An exact determination of Th-232 requires alpha spectrometry.

5.6.3 Overview of indirect determinations

As noted earlier in this Chapter, "direct determination" only applies to actual measured radionuclides. In practice, this is usually done by simple ("basic") or (if available) advanced gamma spectrometry. Other methods, such as radiochemical separation and alpha counting or mass spectrometry, require specialized laboratories and are not available to practitioners in normal circumstances.

To make a qualified (best justified) estimation of the activity concentrations of radionuclides that may contribute significantly to the dose but are not determined by the available gamma spectrometry, the "indirect determination" is a useful tool. For "indirect determination", we are using our basic scientific knowledge (see Chapter 2), previous analysis of samples from similar process streams (see Chapter 3), and the manyfold experience of practitioners to estimate the concentrations of unmeasured radionuclides. Table 5-4 summarizes the approach.

TABLE 5-4: CONCEPT OF INDIRECT DETERMINATIONS

	Basic	**Advanced**
Direct (measured radionuclides)	Simple Gamma Spec (Ra-226, Ra-228, Th-228)	Advanced Gamma Spec (U-238, Ra-226, Pb-210, Ra-228, Th-228)
Indirect (other radionuclides inferred from measures one)	Simple Gamma Spec PLUS U-238, U-234, Th-230, Pb-210, Po-210, Th-232 based on knowledge of radionuclide ratios in different materials	Advanced Gamma Spec PLUS U-234, Th-230, Po-210, Th-232 (Pa-231, Ac-227) based on knowledge of radionuclide ratios in different materials

Table 5-5 and Table 5-6 show the radionuclides that can be determined using both a measured value for another radionuclide and acknowledge of the materials. In these tables, the radionuclides directly determined by gamma-spectrometry are given in the columns below the material names. In the same rows, the radionuclides that can be indirectly determined are given in the left-hand column. The activity concentrations of these radionuclides can be assumed to be equal to those mentioned in the columns. Examples of the method are given in Section 5.6.2.

Because uranium and thorium in NORM precipitated from brines are usually in a background activity concentration, these radionuclides, except for Th-228, can be assumed to be zero and must not be determined.

TABLE 5-5: INDIRECT DETERMINATION OF RADIONUCLIDES (1)

Radionuclide to be determined	Processes or materials (Known radionuclide ratios)			
	Ores, mined minerals	**Slag, fused minerals, ceramics**	**Coal ashes**	**Dust** (from high-temperature processes)
	Radionuclides Measured (Using Basic)			
Th-232	Th-228	Th-228	Th-228	Th-228
U-238	Ra-226	Ra-226	Ra-226	Ra-226
U-234	Ra-226	Ra-226	Ra-226	Ra-226
Th-230	Ra-226	Ra-226	Ra-226	Ra-226
Pb-210	Ra-226	Ra-226	Ra-226	#2
Po-210	Ra-226	Ra-226	Ra-226	#2
	Radionuclides Measured (Using Advanced)			
Th-232	Th-228	Th-228	Th-228	Th-228
U-234	U-238	U-238	U-238	U-238
Th-230	U-238	U-238	U-238	U-238
Po-210	Pb-210	Pb-210	Pb-210	Pb-210
Pa-231[1]	Th-230	Th-230	Th-230	Th-230
Ac-227[1]	Th-230	Th-230	Th-230	Th-230

Notes: 1 - Activity concentration = 0.05 × Th-230; #2 - Ra-226 not suitable for indirect determination. Value is too low.

TABLE 5-6: INDIRECT DETERMINATION OF RADIONUCLIDES (2)

Radionuclide to be determined	Processes or materials (Known radionuclide ratios)				
	Alkaline leaching	**Sulfuric acid leaching**	**Phospo-gypsum**	**Ra-scales Pb-Ra-scales**	**Precipitates from natural gas**
	Radionuclides Measured (Using Basic)				
Th-232	Th-228	Th-228	Th-228	NP	NP
U-238	Ra-226	Ra-226	Ra-226	NP	NP
U-234	Ra-226	Ra-226	Ra-226	NP	NP
Th-230	Ra-226 ·× (Th-228/Ra-228)	Ra-226 ·× (Th-228/Ra-228)	Ra-226 ·× (Th-228/Ra-228)	NP	NP
Pb-210	Ra-226 [3]	Ra-226	Ra-226	Ra-226[5]	NP
Po-210	Ra-226 [3]	Ra-226	Ra-226	Ra-226[5]	NP
	Radionuclides Measured (Using Advanced)				
Th-232	Th-228	Th-228	Th-228	NP	NP
U-234	U-238	U-238	U-238	U-238	NP
Th-230	U-238	U-238 [4]	Ra-226 ·× (Th-228/Ra-228)	U-238	NP
Po-210	Pb-210	Pb-210	Pb-210	Pb-210	Pb-210
Pa-231[1]	Th-230	Th-230	Th-230	Th-230	NP
Ac-227[1]	Th-230	Th-230	Th-230	Th-230	NP

Notes:
1 – For alkaline leaching, activity concentration = 0.05 × Th-230
2 - Ra-226 not suitable for indirect determination. Value is too low.
3 - Based on data in Chapter 3 (0.8 Ra-226) is possible
4 - (0.5 (U-238+R226))
5 - Eventually not conservative and to a lesser extent for Pb-Ra- scales

NP – Generally not present

5.6.4 Suitability of gamma spectrometry for characterization of NORM

An overview of materials from typical processes involving NORM and the methods that are suitable for characterizing the complete radionuclide composition of these materials is given in Table 5-7. This table applies only to solid materials. It shows:

- In many cases, a simple (basic) gamma-spectrometry is sufficient.
- Advanced gamma-spectrometry is required if Pb-210 or U-238 may occur.
- In all cases, the results of the gamma-spectrometry must be supplemented by indirect determination of additional radionuclides based on a knowledge of the NORM.
- Methods other than gamma-spectrometry are needed for characterizing solid materials only in very special cases. Characterizing liquids or organic materials is a specific challenge and not considered in this chapter.

TABLE 5-7: GAMMA SPECTROMETRY FOR CHARACTERIZATION OF NORM. (NOTE THAT IN ALL CASES, THE "INDIRECT" METHOD IS REQUIRED TO OBTAIN A FULL SET OF RADIONUCLIDES)

Sector	Process	Material	Method	Remarks
Mining	mechanical extraction	Ores, Minerals, Coal	Basic	
Oil/gas production	Extraction of liquids	Scales, sludges	Advanced	Determination of U-238, Th-232, Th-230 not necessary
Ore and mineral processing	Beneficiation	Beneficiation products or wastes	Basic	
Pyrometallurgy	Smelting or Sintering	Slag, Sintered or fused minerals	Basic	Note that Pb-210 alone will overestimate
Hydrometallurgy	Sulfuric acid digestion	Phosphate ores	Basic	Th-230 uncertain
	Sulfate precipitates		Advanced	
Coal combustion		Bottom ash and Fly ash	Basic	
Water treatment	Sand or gravel filter	Used filter sand or gravel	Basic	
Gas transport	Precipitation from gas streams	Deposits in pipelines	Advanced	

5.6.5 How does indirect determination affect the dose?

Figure 5-9 shows the effect of using complete ("true") nuclide data sets supplemented by the indirectly determined radionuclides to determine the inhalation dose. For this purpose, dose values were calculated for the four cases:

a. Radionuclides measured by simple gamma-spectrometry ("direct (basic)"),

b. Radionuclides, added according to the rules of the indirect determination approach (Section 5.6.1) based on simple gamma spectrometric results ("Indirect (basic)"),
c. Radionuclides measured by advanced gamma-spectrometry ("direct (advanced)"),
d. radionuclides, added based on the advanced measurements ("Added (advanced)").

For each of these cases, the calculated doses were compared to "true" radionuclide compositions, which is case (d) (with the exception of Po-210-dominated materials). The highest inhalation dose coefficients according to ICRP [129] were used in each case. Results below 100 % indicate an underestimation of the actual dose, and results above 100 % indicate conservative overestimation.

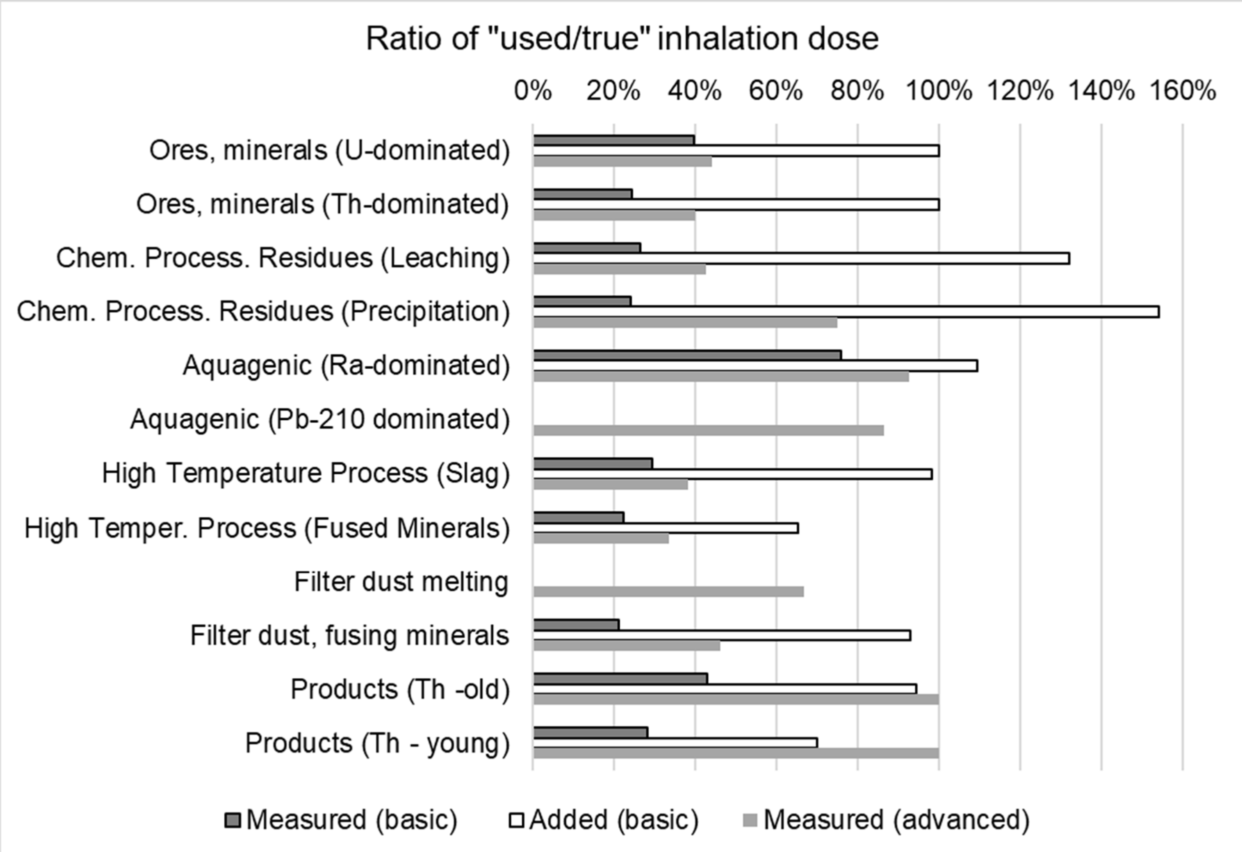


FIGURE 5-9: COMPARISON OF INHALATION DOSES CALCULATED WITH DIFFERENT DATA SETS (EXPLANATION IN TEXT)

The diagram shows that calculating inhalation doses based only on the easily measurable gamma emitters Ra-226, Ra-228, and Th-228 ("Measured (basic)") considerably underestimates the true dose values. Particularly large deviations occur for chemically processed residues (precipitated) like phosphogypsum. One reason of the underestimation is that Th-230 and Pb-210 are "forgotten" in the dose calculation.

On the other hand, the dose is often (conservatively) overestimated if the nuclide vector is schematically supplemented using these "basic" measured values.

5.7 How to measure radon?

Exposure to radon can be an important factor for radiation protection in industries that involve NORM. This section aims to provide the practitioner with preliminary thoughts and methods for radon assessment. Note that Chapter 2 describes the basic principles of radon, thoron, and exposure. The reader is referred to this chapter.

Furthermore, readers should identify any national standards that may apply and refer to IAEA [130] publications.

Measurement should be based on an appreciation of the situation that needs to be characterized. Where there is potential for workers or the public to be exposed to material containing elevated concentrations of naturally occurring uranium or thorium, radon isotopes are likely to be present in the air. For uranium, the isotope is Rn-222 (commonly referred to as "radon"). For thorium, the isotope is Rn-220 (commonly known as "thoron").

The release of radon to the atmosphere depends upon a number of factors, including the porosity of the host material, the density of the material, and the half-life of radon. Some typical values of the radon release rate (also known as the radon flux or emanation rate) of different materials are compiled in the Appendix. If it is necessary to know the values in an individual case, it is usual to undertake measurements.

As described in Chapter 2, the primary hazard does not come from radon. It comes from the dose delivered by the decay products of the radon.

There are many possible parameters that can be measured, including emanation, radon concentration, and radon decay product concentration, for each of the radon isotopes. A knowledge of the measurement technique is therefore critical to ensuring that "you are measuring what you want".

A summary of various techniques is shown below. Note that there are many techniques, and only some of the common ones are discussed.

Radon Emanation

Radon emanation measurement techniques usually measure the rate of change of radon concentration within a closed volume containing the source material. Such techniques are:

- Closed can radon emanation
- Charcoal cans.

Radon at workplaces

For radon at workplaces, an air sample is usually taken either actively (by pumping) or passively (by diffusion), and the alpha decays are counted.

- Integrated measurement can be carried out by / alpha track (SSNTDs), electret, activated charcoal
- Continuous measurement can be done using either passive or active monitors using various detection techniques (electrostatic collection on alpha detector, Lucas cell, ionization chamber (pulsed, current))

Passive devices integrate the recorded decays over time. They are inexpensive but generally require longer measurement times (days to up to 1 year) and do not provide any information about the temporal changes in radon concentration.

Continuous monitors are more expensive than passive devices. They can measure temporal changes in radon, which is an important piece of information for workplaces with good ventilation during active work and none during other times (night, weekend).

Radon decay products

The measurement techniques for radon decay products are based on taking a known volume through a filter and alpha counting the "deposit" on the filter using specific count times. Advanced method use filter and a mesh screen to measure attached fraction on the filter and unattached fraction of radon progeny on the mesh screen. This enables specific radon decay radionuclides to be measured, and using measurement factors, the concentration in air is determined.

Established radiometric methods for the rapid determination of the concentration of short-lived radon progeny (radon daughters) in the air, especially in mines or indoor spaces, include methods by Kusnetz et. al. [131]. This method serves to determine the potential alpha energy concentration (PAEC) at working levels (WL). It is based on the collection of radon daughters on filter paper and the subsequent measurement of alpha activity. Details of the methods mentioned below can be found through internet searches.

Another possibility is a real-time continuous electronic monitor.

When undertaking measurements, other factors to think about are:

- Calibration and quality assurance
- Sampling duration and frequency
- Location and number of measurement points
- Season (or time of year) of measurements and applicability of a seasonal correction factor
- Estimation of uncertainties

An important message is to think about what you want to measure and select the technique that best suits your budget, the level of accuracy, and your resources. When in doubt, ask fellow practitioners.

5.8 Examples

5.8.1 Case 1 - Measurement of dose rates at drums with refractory rubble

Chemically toxic refractory rubble had to be disposed of at a special landfill. The landfill operator has set an acceptance limit of 3 Bq/g for each decay series radionuclide. The rubbish was packed in drums (Figure 5-10, left).

Phase 1 of the project: For a simplified proof of compliance with this criterion, some drums were sampled, and dose rates were measured at the lateral surface of the drums. Based on the analytical results, a (net) dose rate coefficient of 260 nSv/h per Bq/g (Ra-226 + Ra-228) was determined. Additionally, the analytical results demonstrated a uniform nuclide composition, with U-238 as the radionuclide with the highest activity concentration (see Figure 5-10). The relative activity ratio U-238/(Ra-226+Ra-228) is about 1.

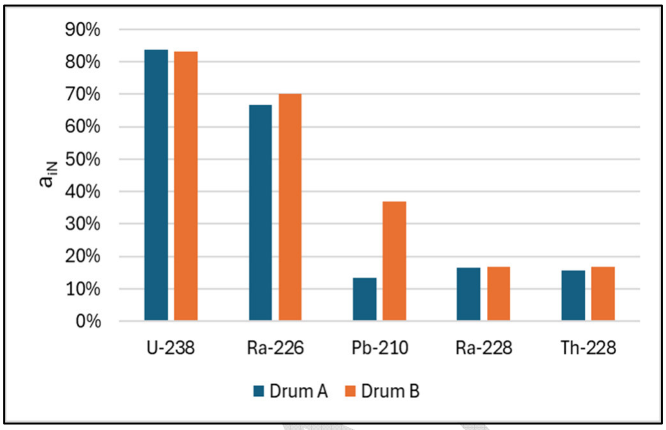
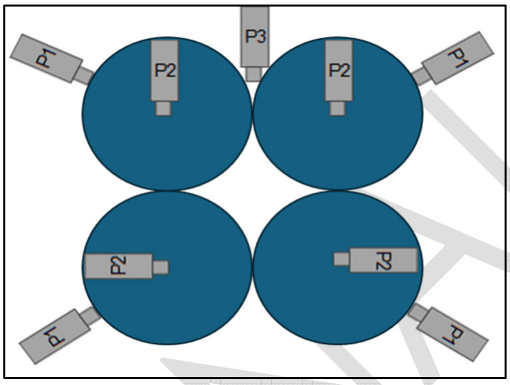


FIGURE 5-10: LEFT: DRUMS WITH REFRACTORY RUBBISH FOR DISPOSAL. RIGHT: NORMALIZED NUCLIDE COMPOSITION OF THE RUBBISH.

Phase 2 of the project: All drums were checked by dose rate measurements at three positions (Figure 5-11, left). P1. Lateral surface at half height of the drum. P2: Central top of the drum. P3: the lateral surface between two drums. Measuring results in position P3 were significantly higher than those in P1 (see Figure 5-11).



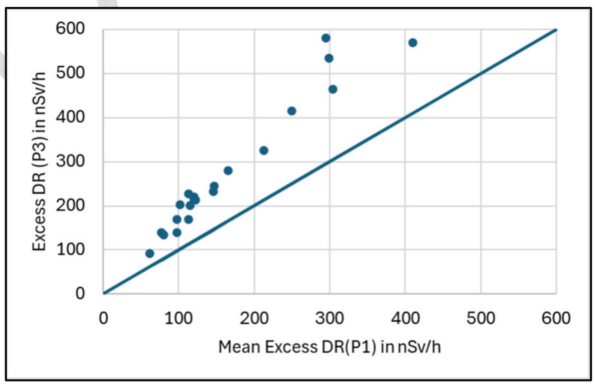


FIGURE 5-11: LEFT: MEASURING POSITIONS FOR DOSE RATE MEASUREMENTS. RIGHT: COMPARISON OF MEASURED DOSE RATES AT

For checking compliance with the acceptance criterium a dose rate threshold was calculated with: C(Max) = C(U-238) = 3 Bq/g = C(Ra-226+Ra-228)

The acceptable excess (net) dose rate (DR(P1)) results from

$$\frac{3\,\frac{Bq}{g}}{260\,nSv/h\;per\;Bq/g} = 780\,nSv/h$$

The maximum excess (net) dose rate measured in position P1 was 410 nSv/h. All drums meet the landfill operator's acceptance criteria and can be disposed of.

5.8.2 Case 2 - Surface contamination monitoring

Surface contamination monitoring is conducted in workplaces for many reasons, including:

- Routine monitoring (as part of an approved monitoring program)
- Sorting of materials for decisions on disposal pathways (to increase recycling and minimize disposal)
- Monitoring to clear for removal from a licensed site (such as sending equipment off-site for maintenance).

This case study describes a large industrial shutdown of a metallurgical processing facility for NORM. The facility was a licensed facility as a planned exposure situation under the local Radiation Control Act. The operational radiation management plan, which was approved by the local regulators, required all plant and material leaving the site to be "cleared".

For this site, the clearance involved two main steps:

- A visual clearance to ensure that the item did not have removable contamination, such as mud or process materials, and
- A surface alpha and beta contamination measurements at various locations on the external surfaces of the item.

The most important preliminary step was to ensure that all items had been physically washed and cleaned before being presented for clearance checking. The site RMP (see Chapter 6) also stipulated that any pumps needed to be flushed with clean water and dismantled for inspection. Similarly, pipes or items with internal surfaces had to be cleaned from the inside and made available for inspection by the qualified technician responsible for the inspection.

All technicians and supervisors who conducted surface contamination clearance checks were trained and authorized by the site radiation safety office and underwent annual recertification. Figure 5-12 shows a photo of a technician during the work.

There were several observations during this shutdown that offer practical lessons.

1. The contractor brought almost 200 tonnes of scaffolding into the operational area; however, the shutdown process ended up with only half of this. However, site rules required all scaffolding to be checked. This was done by taking only a statistical and representative set of measurements; otherwise, it would have been a very long process. For subsequent shutdowns, scaffolding is now placed in an area designated as "clean" by the statutory Radiation Safety Officer (RSO).
   Key Learning? While there is a strong focus on completing work, think and plan for the end of the project to minimize delays.

FIGURE 5-12: A TECHNICIAN CHECKING INSULATION TO DETERMINE ITS DISPOSAL PATHWAY.

2. A significant amount of waste was produced during the shutdown, and the company aimed to recycle as much as possible, with the remainder properly disposed of. The waste was categorized as radioactive, contaminated, non-contaminated (direct to landfill), and recyclable. As a result, all structural waste (such as replaced metal, insulation, and construction materials) was required to be cleaned and then radiometrically checked. This was a big commitment and resulted in some work delays, however, it was generally successful at minimizing radioactive, contaminated, and landfill wastes. This involved assurances about contamination.
Key Learning? It is possible to integrate contamination clearance processes into day-to-day work plans, providing an overall benefit – improved recycling and reduced radioactive waste.

3. When conducting surface contamination checks on equipment in the field, it is important to be "at one with your instrument". As we know, when doing beta contamination checks, there is gamma cross-sensitivity, and also betas can be detected from outside the measurement zone (due to their variable penetration in materials and air). So, care must be taken to ensure that you are looking for and measuring the contamination. As noted above, the first step is always a visual check. "If the item looks dirty, it probably is contaminated". A side benefit of conducting in-field monitoring is the opportunity to communicate with workers, which enables them to ask any questions and also gives them confidence about the clearance process.
Key Learning? Good technicians understand their instruments and also the purpose of what they are doing. They are also the "front line" when communicating with workers, so make sure they are well-trained and supported.

Every site and every shutdown is different, so making sure that work schedules include time for surface contamination checks is important and leads to minimal risk of off-site contamination and increased recycling.

6 RADIATION PROTECTION IN NORM INDUSTRIES: HOW TO MANAGE NORM?

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Contributors: Rainer Gellermann, Stephane Pepin

6.1 Introduction

Radiation is one of a number of hazards that exist in industries that have NORM (see Figure 6-1). It is usually a low exposure hazard; however, this should be confirmed and controls implemented, when required.

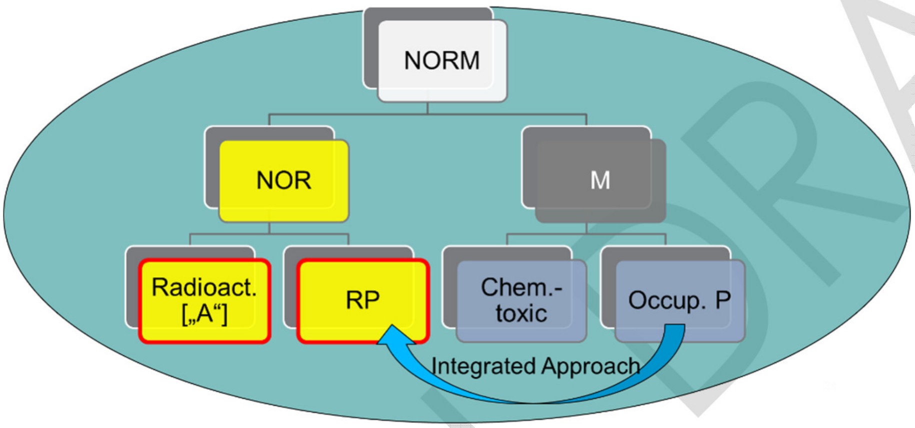

FIGURE 6-1: THE INTEGRATED APPROACH RELATED TO THE NORM-TERM

Management of NORM and its radioactivity involves several components, which are usually gathered into a "management plan" or management system. The purpose of the management plan, or any management of NORM, is to ensure that hazards and risks are managed and that the potential and actual impacts are considered acceptable.

When considering the potential radiological hazards management of NORM, it is important to ensure that controls and management are consistent with the broader management of occupational health, safety, and environmental protection.

However, it is important to ensure that, for radiation protection, there are likely to be specific legislative requirements that will need to be incorporated into any management system.

This chapter provides an overview of the management measures for NORM and provides a number of case studies and examples to show how practical NORM management occurs. This will be from the perspective of both the operator and the regulator.

6.2 What are hazards, what are risks, and how are they managed?

Radiation from NORM should be considered as both a hazard and a risk and therefore requires appropriate management.

Remember that a "**hazard**" is a situation or condition that **is always present** and requires ongoing controls; for example, the safety hazard of rockfall requires strict ground controls to prevent it. For longer-term occupational health hazards, such as exposure to silica in dust, active dust elimination or suppression is required.

Remember that a "**risk**" is usually used to describe a condition, a situation, or an event that **may arise**. For example, the "risk of high dust levels or the risk of a failure of a control". Risk is also defined as a "probability of an undesired event".

The radiation hazards can be managed through good design and ongoing operational and administrative controls, which are verified through monitoring. This is complemented with a program of continuous improvement (which is consistent with the "optimization" principle of the ICRP system of protection).

The radiation risks that arise from something going wrong or changing, therefore, need to be continuously considered as part of the operations risk management processes.

Basic hazard and risk management involves three logical components as follows:

- Identification of the hazards or risks, and this can be done via design reviews, workplace inspections, knowledge of similar operations, and risk workshops.
- Once a hazard has been identified, the next step is to characterize the hazard. This can be complex and involves gaining an appreciation of the magnitude of the hazard. Having a good understanding of materials, material flows, and physical processes aids in characterizing the potential hazard. Characterization and quantification act as justification for the control step.
- Once the size of the hazard is understood, controls can be implemented. Note that in some cases, the control may be a legal requirement and not commensurate with the size of the hazard. In most cases, the aim of the control is to eliminate the hazard or achieve an acceptable level.

6.3 What hierarchy of controls should be observed?

Controlling hazards is based on the hierarchy of controls, which involves:

- Eliminate – the elimination of the hazard by appropriate design.
- Substitute – replacing the material or process with a less hazardous one.
- Redesign – redesign the equipment or work processes.
- Separate – isolating the hazard by guarding or enclosing it.
- Administrate – providing control such as training, procedures etc.
- Personal Protective Equipment – use of properly fitted PPE where other controls are not practical

6.4 Management Systems

Radiation protection is usually subject to its own legislation. The application of this system to a specific plant or facility should be based on developing a radiation management plan (RPM) that meets the legal requirements. It is important to ensure that the RMP is both practical and useful for line management and workers, and also is integrated into the wider site OHS management system.

A NORM-related RPM includes (but is not limited to) the following content:

- Statement of the purpose of the plan
- Identification of all the legislative requirements, including licenses
- Description of the operation and the radiological characteristics (for example, characterization of radioactive materials, emissions, and wastes generated)
- A description of the design and management controls for radiation that are in place.
- A statement of responsibilities and accountabilities for implementation of the plan
- Access to recognized radiation protection expertise and resources
- A description of the radiation monitoring program (covering any worker, public and environmental monitoring)
- An outline of the method for assessing compliance with limits and constraints
- Administrative arrangements (such as reporting, training, Closure considerations

It is relevant to note that the content of a radiation management plan is well defined by the IAEA and regulatory authorities; however, it is equally important that the RMP is practical, readable, and useful for operations personnel. There are many situations where management plans may comply with guidance and regulatory requirements but are never used in practice.

The RPM collects all this information, and all procedures must be written in documents.

The RPM must also describe the control of the effectiveness of the exposure reduction measures (what must be controlled, the method to control, and their frequency). The results of these controls must be recorded.

6.5 How to reduce hazards and risks?

6.5.1 Overview

As summarized in Section 3.3 NORM can be in different forms and in different workplaces. Due to the different forms of the NORM, the exposure pathways can be:

- external exposure by irradiation,
- internal exposure by inhalation (dust and radon),
- internal exposure by inadvertent ingestion,
- internal exposure by wounds.

The principles of radiation protection for external exposure are by

- limiting the exposure time,
- increasing the distance between sources and workers, or
- implementing shielding.

The objective of reduction measures for internal exposure (inhalation, inadvertent ingestion, and wounds) is to reduce the dust rate/radon or the exposure time to the dusty atmosphere/radon.

These measures concern normal operations, maintenance operations, and dismantling operations.

6.5.2 Storage and handling of NORM

There is usually dust and scattering of material on the ground around the storage of bulk NORM (raw materials, products, residues, and waste). Thus, handling of these bulk NORM, especially with trucks, leads to the spread of radioactivity in the plant. To limit or even avoid the spread of NORM in the plant, the following good practices can be put in place:

- washing the wheels of trucks before leaving storage,
- tarping of the trailer.
- obligation to slow down the truck speed in case of high wind situations.

To limit dust or radon concentrations, the operator can install ventilation systems. In case of high dust levels, it is necessary to implement a filtration system limiting the amount of dust released into the air. But this filtration system generates waste that needs to be managed. Furthermore, this filtration system requires maintenance, which generates occupational exposure.

To optimize this collective protection equipment, it is possible to put in place an automatic tarping to keep the operator away from the source and reduce exposure time, but the disadvantage of this equipment is its cost.

An option to limit occupational exposure during handling is conditioning NORM in containers (for example, big bags).

In the case of NORM storage with a high dose rate, it may be necessary to install walls around the storage to limit external exposure for people working or walking nearby.

6.5.3 Processing of NORM

For the introduction of the materials in the process, good practices may be:

- the screening of the materials as fine as possible
- the adequacy of the stirring blades to facilitate the transfer of the materials.

These measures allow for avoiding clogging of troughs, and so, it is not necessary for the worker to take action (so the operator is not in contact with the source and not exposed to dust)

If NORMs are transported on conveyor belts, a good practice may be to install hoods on the conveyor belts to reduce dust generation. However, this can generate significant maintenance requirements.

If the worker must control a process step by looking inside the equipment, a good practice is to adapt the concerned equipment. For instance, it is possible to put a window on the equipment (for example, tank, vessel, rotary filter); this modification allows the worker not to open the concerned equipment. This modification can be associated with lighting inside the equipment and a quick system for sliding the walls. These last modifications make the intervention easier. All these measures allow a reduction of exposure time (due to the minimization of the operator's intervention in contact with the equipment).

To avoid projecting NORM onto workers, transparent protection (e.g., plexiglass) can be put in place.

As for storage in buildings, the building where the industrial process takes place must be ventilated to limit radon concentrations or dust rates. If necessary, a filtration system must be installed to limit atmospheric discharges into the environment.

For dusty workplaces, mobile or fixed vacuum systems can be put in place. Furthermore, periodic cleaning helps limit the amount of dust in the workplace. This cleaning can be done by vacuum systems or with water. The disadvantage is the production of solid waste or liquid effluents.

6.5.4 Treatment and conditioning of residue/waste

When waste treatment uses a filter press, a good practice is to automate the filter with the installation of "big-bags" of large capacity (with a chute), with a geometry adapted to dust capture, and automatic weighing with the servitude of the filling valve.

This measure may reduce the operator's exposure time by a factor of 3. The disadvantage is the cost.

6.6 Administrative Controls

In some cases, zoning is necessary for radiation protection. These zones can be put in place because of the risk of irradiation or the risk of contamination. These are supervised areas or even controlled areas.

6.6.1 Delineation

The industrial plants involving NORM have not been designed taking into account the radiological risk. In this case, the radiological zoning is of the "leopard spots" type.

In this case, the physical delineation of these areas may be difficult. Some good practices for the areas' delineation may be:

- lines and surfaces painted on the floor,
- chains with the specific signs,
- walls (for specific storage).

In some cases, the source is confined to generally enclosed equipment (such as tartars in a gas scrubber). In this case, the area is delimited by the equipment itself and the operator must install appropriate signage on the equipment.

6.6.2 Controlled Access

Access to the supervised areas and controlled areas, is subject to conditions. All workers in an installation are not "classified" due to exposure to ionizing radiation. However, their workplace may require punctual access or regular crossing of a supervised or controlled area. Changing their workplace to avoid regular crossing of a controlled area could expose them to other risks.

It is, therefore, necessary to determine, on a case-by-case basis, and with all the persons concerned (the concerned worker(s), the radiation protection expert, the radiation protection officer, the competent employee for the other risks, the occupational physician, etc.) the changes to take into account all risks.

If the worker is considered as "not exposed" and must access supervised areas or controlled areas (green or yellow), then the employer puts in place provisions to ensure that the dose of this worker does not exceed 1 mSv/year. These provisions are at least the traceability of entrances to the supervised area and controlled area, the description of the performed work, and its duration for each entrance.

An operational arrangement to ensure that the dose remains below 1 mSv/year or an operator-set dose constraint is based on dose rate measurements and an operating time. For example, in the case of equipment with a dose rate of 4 µSv/h, the operator sets a maximum duration of worker intervention on the equipment of 20 hours to respect the dose constraint he has set.

6.6.3 Individual protection equipment

It is necessary to ensure that all the individual protective equipment that a worker must wear to protect himself against all risks does not hinder the work to be done, leading de facto to a deterioration of the protection of the worker against some other risks (such as the risk of disruption of movement, the risk associated with mechanical handling, the risk related to thermal environments, etc.). In order to limit this problem, a reflection must be carried out on the compatibility of some equipment against several risks. For example, the choice of gloves or clothing material can help protect against chemical and radiological risks. In the same way, it is possible to consider that the mask has a synergistic character against dust, chemical substances, radioactive aerosols, and particulate radon progeny.

To avoid transferring NORM into wounds, there must be no contact with NORM.

To avoid or limit internal exposure (inadvertent ingestion, wounds) or skin contamination, wearing gloves may not be sufficient. Indeed, workers may have to put on and take off their gloves several times a day and, therefore, are likely to contaminate their hands. Therefore, a good practice is to combine the wearing of gloves with regular washing of hands and exposed skin (arms, face, neck).

The service providers must identify their individual protective equipment. So, the operator must inform service providers of the presence of NORM in their workplaces and discuss individual protective equipment with them.

6.7 Information and training of workers

The Table 6-1 suggests examples for the content of information and training for workers. The level of detail is greater in the case of training.

Information and training are also applicable to the service providers. So, the operator must inform the service providers about the presence of NORM in their workplaces.

TABLE 6-1: INFORMATION AND TRAINING

Content of information	Content of training
• Natural sources of radiation ▪ Origin of NORM and decay series ▪ NORM in the plant ▪ Forms and appearance • Practical definition of occupational exposure • Principles of radiation protection and safety ▪ Principles ▪ Occupational radiation protection ▪ External and internal exposure • Responsibilities of workers • Safe operating procedures • Emergency procedures if any • Name and contact number of the radiation protection officer	• Natural sources of radiation ▪ Origin of NORM and decay series ▪ NORM in the plant ▪ Forms and appearance • Practical definition of occupational exposure • Principles of radiation protection and safety ▪ Principles ▪ Dosimetric quantities ▪ Dose limits and application of annual limits ▪ Reference levels ▪ Occupational radiation protection ▪ External and internal exposure • Responsibilities ▪ Responsibilities of employers ▪ Responsibilities of workers • Safe operating procedures • Emergency procedures if any • Name and contact number of the radiation protection officer

6.8 Practical guidance for regulators

6.8.1 Which NORM is worth being regulated, and who is in charge of regulating NORM?

A prerequisite to regulate NORM is to develop some understanding of the issue: this requires the development of a national inventory of activities involving NORM. The development of such an inventory is an iterative process - a full knowledge of all activities involving NORM is not required to start regulating NORM. The regulator may choose to first focus on a limited set of activities involving NORM, where the exposure risks are known to be significant.

Review of regulatory infrastructure: a component of the national policy regarding NORM is to define which regulator is in charge: it may be the nuclear regulator, the environmental regulator, etc. or a combination of them. In any case, it is important that all regulators involved are aware of the tasks and responsibilities of each of them and communicate with each other.

<u>How to regulate?</u>

Regulations regarding NORM should take into account a graded-approach (the regulations should be commensurate with the risk) and the integrated approach (regulations regarding NORM should be consistent with other relevant regulations regarding health & safety, environmental protection and waste management; the regulatory controls put in place by these other existent regulations should be taken into account when developing and implementing the radiation protection strategy).

BOX 6-1: EXAMPLE FROM USA

In WV, a fracking centralized treatment facility was permitted and operated for a few years before going bankrupt and abandoning the site. Turns out - this discharge permit for this facility DID NOT INCLUDE RADIUM. Some pinhead wrote the permit using usual petroleum parameters but did not include rads. Concentrations of sludge and abandoned piles of stuff were in the thousands of picucuries per gram and external readings topped 5 mR/h at this location. It had been taken over by teens who were partying there (beer cans, mattresses…). It was not fenced. A journalist exposed it and then EPA has taken it over. Hard lessons ...

Periodic review of regulations based on lessons learnt and stakeholders' involvement: regulations are dynamic as new industrial activities may emerge and others fade out - feedback from field experience, inspections, stakeholders' comments and complaints should regularly be reviewed and taken into account in revision of the regulations.

6.8.2 Components of the regulatory framework

The main components of a regulatory framework for NORM are defined e.g. in IAEA requirements, in particular IAEA BSS (GSR Part 3 [5]) or IAEA Safety Guide SSG-60 [132]. They include:

- Definition of terms - taking care of the consistency with definitions in other regulations.
- Interaction between regulators: set up communication channels and/or a memorandum of understanding.
- Systems of regulatory control: notification, registration, licensing, and definition of regulatory criteria.
- Exemption and clearance.

6.8.3 Implementation

Several examples of the practical implementation of NORM regulations have already been described in Chapter 4. For activities involving NORM that are not exempt from any control, the requirements on NORM activities may cover the following aspects:

Radiation protection program, systems of control, and monitoring.

Controls already in place for non-radiation aspects must be considered.

The extent of these controls depends on the magnitude of the risk. Generic controls will generally be implemented through registration. More specific and stringent controls may be implemented through licensing.

To verify that requirements of the authorization (registration or license) are well-implemented in practice, an inspection and enforcement policy must be carried out. The findings of the inspections are one of the key elements of the review process for the regulations and their practical implementation: Are the regulatory criteria appropriate, do they provide a sufficient level of radiation protection, and are they well understood by the operators?

The implementation process and the appropriateness of the authorizations have to be reviewed periodically: are the authorizations still up to date?

Did new processes or new raw materials appear?

Did the ownership of the activity change or the persons in charge of the practical implementation on-site?

This review process must consider the entire life cycle of the facility, including the development of new processes, evolution in the management of residues, decommissioning aspects, and long-term management of waste and residues.

The regulators' objective is to ensure that a radiation protection program is established by the employer, well applied by the workers, and controlled by the operator. This verification is realized during inspections.

An inspection can be divided into two parts: a no-field part (in a meeting room) and a field part. The following table gives examples of topics verified in these two parts.

TABLE 6-2: KEYWORDS FOR IMPLEMENTATION OF RP IN OPERATIONAL PROCESSES

	No-field part	**Field part**

Radiation protection for workers	• Radiation protection officer
	• Nomination (letter that must mention the duties)
	• Training
	• Prior radiological assessment
	• Radiation protection program
	• Written procedures
	• Control of effectiveness of the reduction measures
	  ○ Adequacy of the method
	  ○ Adequacy of the frequency
	  ○ Results of the previous controls
	• Dosimetry monitoring
	• Health surveillance program
		• Implementation of reduction measures
		• Individual protection equipment
		• Identification of the radiological risk areas
		  ○ Delineation
		  ○ Access conditions
		• Workplaces' monitoring
		  ○ Location
		  ○ Adequacy

Radiation protection for public members / environment	• Discharges
	  ○ Identification of discharges pathways
	  ○ Discharges quantities
	  ○ Impact assessment
	• Environmental monitoring plan
	• Waste management
		• Discharges monitoring
		  ○ Location
		  ○ Adequacy
		• Environmental monitoring
		  ○ Location
		  ○ Adequacy
		• Waste storage

In some countries where there is no radiation protection expert, the regulators realise the following tasks during inspections:

- establishment of the radiation program (in collaboration with the operator) or review of the radiation protection program,
- realization of measurement in the different workplaces of interest,
- presentation of the measurement results from the previous inspection
- advice for the different radiological issues and filling out the regulatory form (like the notification form if this notification is annual)

6.9 Tips for practice: Overview of Practical Control Measures

This section provides a collection of potential controls that can be utilized for situations with NORM.

6.9.1 Mining Sites

- Underground mines have ventilation systems that consider radon and radioactive dusts along with other hazards such as silica, inert dust, diesel particulates and heat.
- Design ventilation systems so that they always ensure that workers are in fresh air rather than recycled or contaminated air.
- For open-cut mines, ensure that dust generation is minimised or controlled through the use of water sprays.
- Place stockpiling of NORM in areas downwind of occupied workplaces.
- Aim to minimize multiple handling of NORM material – each movement is an opportunity to generate dust.
- Where there is NORM with elevated gamma levels, aim to locate workplaces in low gamma radiation areas.

6.9.2 Processing Facilities

- Bunding of tanks and process vessels, to control spillages
- Hose-down facilities and sumps to aid in clean up
- Vacuum systems where dry process material cannot be cleaned up with hoses and water
- Covering conveyors and materials transfer points
- Wet scrubbing systems for exhaust capture
- Ensuring ventilation of enclosed building (through air movers, roof ventilators, large doors or louvred panels)
- Placement of offices, lunch and control rooms away from stockpiles of materials
- Establishment of a dedicated wash-down or decontamination facility, with containment of water
- Change-room facility for workers

6.9.3 Operational and Administration Controls

- Induction and training of workers
- Conducting effective toolbox meetings, with open discussion
- Use of audited safe work procedures
- Use of safety procedures tools such as job hazard analyses
- Enforcement of disciplinary measures for deliberate violation of safety rules
- Identification of radiation work areas
- Establishment of smoking areas away from the workplace
- A radiation monitoring program
- Waste management procedures and practices.
- Access to qualified advice and guidance on radiation protection.

7 NORM WASTE TREATMENT

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7.1 What is NORM waste?

7.1.1 What is waste, and what does " NORM waste " mean?

In its Glossary [133], the IAEA describes "**waste**" as "*Material for which no further use is foreseen*" and "**NORM waste**" as "*NORM for which no further use is foreseen*." These rather universal definitions are based on a material's usability and are independent of the radioactivity.

Depending on its chemical composition, such waste may be classified as "**hazardous waste**" if its toxic components pose a danger to human health or may cause environmental contamination.

However, all liquid or gaseous effluents discharged into the environment, because further use is neither foreseen nor possible, can be seen as waste. Therefore, the term waste is applied differently.

In the United States, waste is primarily defined by the Environmental Protection Agency (EPA) under the Resource Conservation and Recovery Act (RCRA) as "*any garbage, refuse, sludge from a wastewater or air pollution control facility, or other discarded material.*" This definition includes solid, liquid, semi-solid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, as well as community activities.

In South American countries, "waste management" is strongly focused on municipal solid waste (MSW) or domestic solid waste (DSW) that is generated, collected, and managed by local authorities [134]. The main source of NORM waste in this region is mining or milling waste, which is frequently regulated as part of the mining and milling processes. A similar situation is held in Africa.

In the Asia Oceania Region, the diversity of national approaches is high and depends on the role of mining and milling, and the industrial development.

In Europe (EU) waste is defined as *any substance or object that the holder discards, intends to discard, or is required to discard* unless it can be repurposed. Currently, in the EU, the management of waste is governed by the Directive 2008/98/EC [135] on waste and the Directive 2006/21/EC on the management of waste from extractive industries [136]. These directives define all options for waste treatment, including recovery and disposal. Liquid or gaseous discharges are not considered to be waste and are regulated by specific laws.

A particular type of waste is mining waste. Mining waste is the high-volume byproduct generated during the extraction and first processing of mineral resources. It consists of non-valuable materials for which "further use" is not foreseen, and which must be disposed of close to the mining site. Typical types of mining waste are

- Overburden: Soil and rock removed to reach ore deposits.
- Waste Rock: Material removed during excavation that is not economical to process.

- Tailings: Fine-grained slurry or solid waste left after crushing and processing ore.

7.1.2 What is radioactive waste?

According to the IAEA Glossary, **radioactive waste** is a radioactive material in gaseous, liquid, or solid form for which no further use is foreseen.

In Figure 7-1, a simplified scheme shows how materials from an industrial process may become radioactive waste.

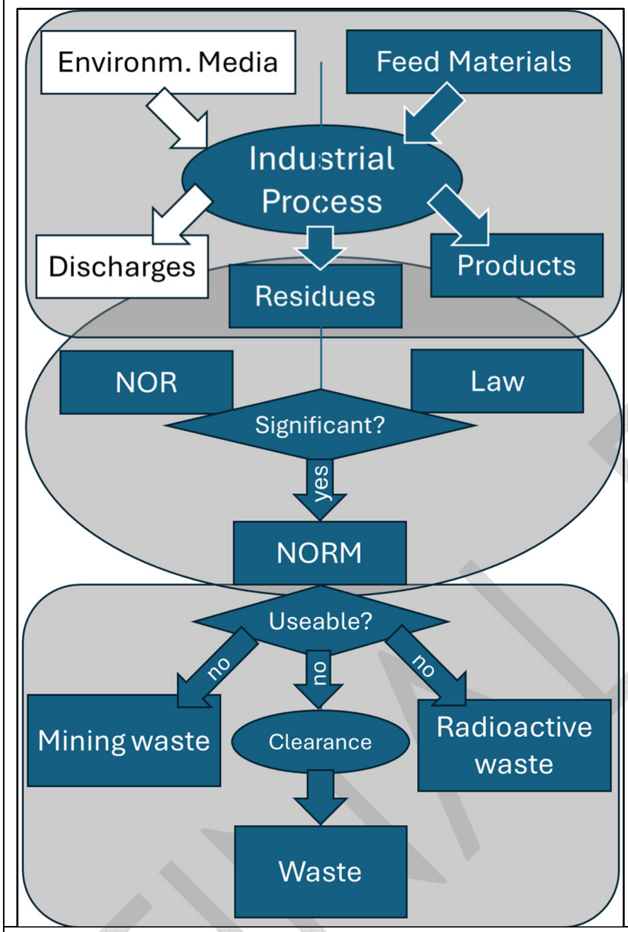

FIGURE 7-1: SIMPLIFIED SCHEME ON RELATIONS BETWEEN INDUSTRIAL PROCESSES, NORM, AND WASTE

There are three blocks to consider:

1. There is an industrial (or mining, milling) process. In this process, feed (raw) materials are treated and converted to marketable products. Typically, non-marketable **residues** are also generated. Furthermore, environmental media (water, air) are part of the process and are released in the environment as liquid or gaseous effluents (discharges).

The radioactivity of the feed materials contributes to NOR concentrations throughout the process. However, it is not decisive for the generation of radioactive waste. As it was shown in Chapter 5. #, the transfer of radioactivity in small mass streams generates high NOR concentrations. If such processes occur, they significantly influence the radioactivity of the residues.

2. A key prerequisite for the generation of radioactive waste is that the residues are subject to regulatory control as a **radioactive material** (or a radioactive substance).

The term "radioactive material" is applied to material designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity (IAEA Glossary). To be classified as radioactive material:

- The total activity A and the activity concentration C must exceed the corresponding exemption values A*, C*.
- The material must be included in the regulatory scope.

In particular, the latter item is not self-evident in the case of NORM. In some countries, the regulatory scope for NORM is based on a positive list rather than on activity concentration alone. If such a "selective approach" is applied, materials with activity concentrations above the exemption values are considered to be non-radioactive in a legal sense.

According to the definition of NORM given by the IAEA (see Chapter 2), which is not shared by all countries and not by each person who talks about NORM, residues are "NORM residues" only if their radioactivity is classified by a state regulator as "significant".

3. If residues are classified as NORM residue and are not further usable, the operator is responsible for safe disposal. This disposal can be made
   - As **mining (and milling) waste** (e.g., overburden, waste rock, tailings of on-site processing or water treatment).
   - As **non-radioactive (common) waste** after an authorized clearance.
   - As **radioactive waste**, i.e., waste that is handled and disposed of under a radiation protection regime.

Note:

The term "radioactive waste" is a particular term for waste that is stored, handled, treated, and disposed of under a state radiation protection regime. Although very common, this term should **not** be applied to NORM waste in general. It is an established practice in many countries that clearance criteria are established, and NORM waste with low or very low levels of radioactivity can be released from control and disposed of according to the national waste regulation, i.e. as conventional (non-radioactive) non-hazardous or hazardous waste (see Section 7.#).

The term "mining and milling" is referred to by the IAEA (Glossary) to mining of uranium or thorium ores, but also in conjunction with other substances being mined, in amounts or concentrations that require radiation protection measures to be taken as determined by the regulatory body, and processing of radioactive ores from such mines to produce a chemical concentrate.

Mining and milling waste can be used to describe all non-useable materials that occur or are generated during the operation of a mine, regardless of the type of ore. The specific conditions of mine sites and the regulatory regime under which a mine is licensed and operated require a high degree of flexibility in applying the regulatory framework.

7.1.3 How can NORM waste be categorized?

In its Standards Series publication GSR-1 [137], the IAEA has introduced classes of radioactive waste. These classes were derived from international discussions on the final disposal of radioactive waste contaminated with man-made radionuclides. For that reason, the IAEA terms and waste classes should be applied to NORM waste, not in a formal but flexible manner.

In the following, the IAEA terms regarding NORM waste are cited and commented on.

Long-lived waste. Radioactive waste that contains significant levels of radionuclides with a half-life greater than 30 years.

Comment: With the exception of Pb-210 (Po-210) dominated dust, most other NORM waste is long-lived waste. Therefore, the many restrictions regarding "long-lived waste" in the IAEA Standards (see below) should be checked for NORM waste in a proportionate manner.

Exempt waste (EW). Waste that meets the criteria for clearance, exemption, or exclusion from regulatory control for radiation protection purposes.

Comment: (#& in: exempt – out clearance + approval)

Very low-level waste (VLLW). Radioactive waste that does not necessarily meet the criteria of exempt waste, but that does not need a high level of containment and isolation, and, therefore, is suitable for disposal in landfill-type near-surface repositories with limited regulatory control. Such landfill-type near-surface repositories may also contain other hazardous waste; typical waste in this class includes soil and rubble with low levels of activity concentration. Concentrations of longer-lived radionuclides in very low-level waste are generally very limited.

Comment: The last sentence needs a "soft" interpretation regarding the phrase longer-lived radionuclides are very limited because radioactivity of NORM waste is normally caused by longer-lived radionuclides. Nevertheless, NORM waste is often considered VLLW, which does not require high-level containment and isolation, and is, in many countries, allowed for disposal in landfills. Exceptions are residues with high activity concentrations, such as scales from the oil and gas industries, geothermal energy production, or specific waste from titanium dioxide production.

In mining, onsite processing [P1] and ores and raw mineral processing [P2] (see Section 3.1), the volumes of NORM waste can be particularly significant.

Low-level waste (LLW). Radioactive waste that is above clearance levels, but with limited amounts of long-lived radionuclides.

Low-level waste requires robust containment and isolation for periods typically of up to a few hundred years and is suitable for disposal in engineered near-surface disposal facilities.

Low-level waste may be so classified on the basis of waste acceptance criteria for near-surface disposal facilities.

Comment: Pursuant to the IAEA, LLW may include short-lived radionuclides at higher levels of activity concentration, but long-lived radionuclides only at relatively low levels of activity concentration that require only the levels of containment and isolation provided by a near-surface disposal facility.

Intermediate level waste (ILW). Radioactive waste that, because of its content, in particular its content of long-lived radionuclides, requires a greater degree of containment and isolation than that provided by near-surface disposal.

Typical characteristics of intermediate-level waste are levels of activity concentration above clearance levels.

However, intermediate-level waste needs no provision, or only limited provision, for heat dissipation during its storage and disposal.

Intermediate-level waste may contain long-lived radionuclides, in particular, alpha-emitting radionuclides that will not decay to a level of activity concentration acceptable for near-surface disposal during the time for which institutional controls can be relied upon.

Waste in this class may therefore require disposal at greater (intermediate) depths, of the order of tens of metres to a few hundred metres or more.

Intermediate level waste may be so classified on the basis of waste acceptance criteria for near-surface disposal facilities.

Comment: NORM is classified ILW depending on national standards. E.g. in the Netherlands NORM waste with # is stored in the national repository COVRA. In France ##.

High-level waste (HLW) will not be generated during NORM processing.

7.1.4 Special case: Phosphogypsum

Because the production of one ton of P_2O_5 as phosphoric acid results in an approximately 4–6 ton dry mass of phosphogypsum (IAEA 2013), the worldwide processing of phosphate rocks generates more than 1 billion tons of phosphogypsum annually that is up to 5 times more than total worldwide use of natural gypsum in construction.

Figure 7-2: Phosphogypsum waste pile in Jordan

(Photo: J. Hondros)

The properties of phosphogypsum offer possibilities for use in agriculture, construction of buildings or roads, and coastal fortification (IAEA, 2013).

In its Report on Radiation Protection and Management of NORM Residues in the Phosphate Industry, the IAEA states that "*concerns about its radioactivity content and, to a lesser extent, its heavy metals content, have led to restrictions on the use of phosphogypsum in some markets, even though such concerns do not always have a proper scientific foundation.*" (IAEA 2013, p. 112). This also holds in our experience in cases where the radioactive contamination is lower than 1 Bq/g, that is, phosphogypsum complies with the general exemption values established in radiation protection.

A radiological risk assessment would clearly show that the risks are low in many circumstances.

7.2 How does NORM waste become common waste? (The concept of clearance)

As we explained in Section 2.2.3, NORM means *material containing no significant amounts of radionuclides other than naturally occurring radionuclides.* The decisive word that makes NOR to NORM is "significant". According to this definition, NORM contains NOR in an amount that is considered significant (by state regulators) from a radiation protection point of view.

Vice versa, the radioactivity of NORM can be considered insignificant, and NORM may consequently be released from regulatory control. The authorization process that approves "*which sources, including materials and objects, within notified practices or authorized practices may be cleared from regulatory control*" is named "clearance". According to IAEA GSR Part 3 [#&], the term 'clearance' is used in relation to sources, including materials and waste but not to the release of sites from regulatory control.

The general criteria for clearance are [GSR Part 3 Paragraph I.10] that:

a) *Radiation risks arising from the cleared material are sufficiently low as not to warrant regulatory control, and there is no appreciable likelihood of occurrence for scenarios that could lead to a failure to meet the general criterion for clearance; or*

b) *Continued regulatory control of the material would yield no net benefit, in that no reasonable control measures would achieve a worthwhile return in terms of reduction of individual doses or reduction of health risks.*

For NORM GSR Part 3 Paragraph I.12 states:

"For radionuclides of natural origin in residues that might be recycled into construction materials, or the disposal of which is liable to cause the contamination of drinking water supplies, the activity concentration in the residues does not exceed specific values derived so as to meet a ***dose criterion of the order of 1 mSv in a year****, which is commensurate with typical doses due to natural background levels of radiation."*

The tolerable dose is higher by a factor of 100 than that used for man-made radionuclides, where 10 µSv in a year is applied.

Some examples of national regulations that interpret the clearance concept in different ways are presented in Section 7.7.9.

7.3 What types of NORM waste occur?

In practice, typical NORM waste includes:

- Solid mineral waste (coarse to fine particles)
- Dust (very fine particles)
- Sludges
- Liquid waste (collected, not discharged as wastewater or other effluent)

In the Table 7-1, typical wastes from industries involving NORM are compiled. (A similar table is contained in IAEA SSG-60 [138]).

TABLE 7-1: TYPICAL WASTES GENERATED IN INDUSTRIAL SECTORS RELEVANT FOR NORM (CF. TABLE 3-1)

Industrial sector	**Typical wastes**
Extraction of rare earth elements	Mining waste, overburden, tailings from on-site milling and processing
Production of thorium and its compounds	Contaminated supplies (wipes, face masks, gloves)
Production of niobium, ferro-niobium;	Slag, filter dust
Use of thorium and its compounds	Contaminated supplies (wipes, face masks, gloves). Thoriated scrap.
Mining of ores other than uranium ore	Mining waste, overburden
Production of oil and gas;	Scales, sludge, and contaminated installations
Manufacture of titanium dioxide pigments	Filter units, scales, sludge, and contaminated installations
The phosphate industry	Phosphogypsum, scales (incrustations)
The zircon and zirconia industries;	Used refractory materials
Production of tin, copper, aluminum, zinc, lead, and iron and steel;	Slag, filter dust
Combustion of coal	Ashes, Filter dust. Refractory waste from the maintenance of heating vessels
Water treatment.	Filter sand or gravel; sludges; U-Ion exchangers; scales
Geothermal energy production.	Scales, sludges
Cement production and maintenance of clinker ovens.	Refractory waste from the maintenance of heating vessels
Building materials (including building materials manufactured from residues or by-products)	Construction waste; dust from ceramic firing
Coal mining	Mine water sediments in tailing ponds or excavated sediments from water courses

It must be emphasized that the problem of NORM waste is relatively new to many industries currently accounted for involving NORM. Given that industries involving NORM in many cases have existed for decades, and materials, residues, or waste currently referred to as NORM did not appear suddenly and often have existed since a relevant industry was set into operation.

A particular case in waste management is waste generated during mining operations. Some assessments on this case are given in the next section.

7.4 Why are wastes and residues from the mining industry particularly?

The largest volumes of NORM waste generated in the industrial production chain (see Figure 3.#) stem from mining and milling. Massive volumes of materials are mined and processed by various means to extract, concentrate, and purify minerals and other resources needed in the industrial process chain (Section 3.#).

Unlike other parts of the industrial process chain, the locations where mining takes place are determined by mineral or other resource deposits and cannot be chosen (to a large extent) freely. As a result, the locations where mining waste is disposed of can also be chosen only to a limited extent. Therefore, mining and milling are commonly licensed under a special regulatory regime ("Mining Law") that includes the treatment and disposal of waste.

While uranium mining targets radionuclides but is not considered NORM, other mining and processing operations of non-radioactive elements (metals) or minerals may concentrate NOR or change their location. Non-usable materials of such mining include:

- The overburden that is removed to gain access to an underground resource and the remaining rock with an uneconomic grade of the valuable minerals (waste rock) are usually disposed of in "waste rock storage facilities" or waste rock dumps. If the concentration of NOR in the waste rock exceeds the surrounding surface concentrations, then a change in the radiological situation has occurred.
- Tailings are fine sand-like particles left over after ore has been crushed and processed in a mill as part of beneficiation, and partly also chemical treatment on the mining site. Tailings are usually disposed of in containment facilities, sometimes referred to as "tailings ponds". Currently, most tailings ponds are designed with containment dams; however, this was not always the case historically, and a number of uncontained tailings have contaminated areas around the world and are usually classified as legacy sites.
- Water treatment residues when high-salinity or strongly acidic mine water is present. Similar to tailings, a direct, untreated discharge of such mine water can result in contaminated sediments that may form radioactive legacy sites.

Not mining but in close relation to mining is the processing of mined ores or minerals at the mining sites. Such processing is advantageous and cost-efficient because it avoids transporting large amounts of material to a processing plant. An example of such processing is fertilizer production from phosphate ore.

Examples of NORM residues generated from mining, milling, and on-site processing are:

- Phosphogypsum, the residue of the fertilizer industry, with approximately 5 kg produced for every kg of fertilizer [REF?]. Massive waste piles exist in many places in the world, and they contain elevated concentrations of Ra-226.
- *Amang* is a residue of tin mining and processing in Malaysia. It contains ilmenite, quartz, tourmaline, zircon, and monazite, and is frequently radioactive to a significant amount [139]. It is considered a byproduct and used for the production of rare earth elements.

- Residues of saline mine water treatment are known in Poland [140] and Germany. They are enriched in radium.
- Acidic ferruginous mine water is formed when pyrite in coal or metal mines is exposed to air and water, oxidizing to produce sulfuric acid and dissolved ferrous ions. Such waters may contain high concentrations of uranium and thorium. Treatment of water for dissolved iron removal results in sludges that may also contain uranium and thorium in radiologically significant amounts.

The common features of mining waste are:

- Mining is commonly regulated by special law, and the storage and disposal of waste is done according to site-specific possibilities. Because of this, NORM residues from former mining operations are often legacy sites that require consideration from an environmental and radiation protection perspective.
- Overburden, waste rock, and tailings may occur in very large volumes of material, up to hundreds of millions of tonnes.
- If the activity concentrations of the waste materials are elevated compared to where the material is to be disposed of, the exposure situation of workers or members of the public is changed.
- In many cases, the radionuclide content may not exceed the 1 Bq/g criterion; however, the material may be much higher in radioactivity than the surrounding area. For example, the waste rock might contain 0.5 Bq/g; however, the natural background levels in the soil might only be 0.05 Bq/g. In this case, it is important to consider the possible impacts, and even though the material does not exceed 1 Bq/g, an assessment should be conducted. Based on the assessment, a decision can be made on whether additional controls are necessary.

  Note that in this example, this does not mean that the material should be regulated for its radioactivity; however, its impact does need to be assessed.

As shown in Chapter 3, chemical processes act on radionuclides. Acid will leach uranium and thorium into solution and percolate from waste materials or be captured in any water management system. The acid can simply be generated by rain interacting with sulfur-bearing minerals in the waste materials. This is also known as acid mine drainage (AMD) or acid rock drainage (ARD). The drainage water in this case will be elevated in uranium (as well as any other metals or chemical elements that are acid-soluble).

In a similar manner, the surface storage or disposal of large quantities of waste rock can lead to other potential radiological impacts. If there are elevated concentrations of radionuclides above natural background levels, there will be an increase in the emission of radon from the area of the material. This may lead to a localized increase in radon concentrations under certain meteorological conditions. Similarly, dust emissions from the material can lead to potential inhalation doses and, therefore, radionuclide deposition into the wider environment.

It is important to note that the radiological consequences will be low; however, characterizing the impacts provides confidence for all stakeholders and can be used to make decisions on the need for any controls.

In practice, all waste rock storage or disposal facilities should undergo an impact assessment that includes radionuclide characterization and their final fate. However, it is important to remember that, in almost all cases, the other physical and chemical characteristics of these large volumes and masses of material can pose hazards that exceed any radiological hazards.

Key messages:

- It is a common mistake to neglect the radiological properties of waste rock or overburden, especially when the target minerals are known to be associated to uranium or thorium [141or stem from deeper horizons.
- Always ensure that the waste rock is characterized radiologically and the characterization of the material, making sure to focus on more than just the radiological aspects.
- Consider radon (Rn-222) releases from large mining dumps as a possible exposure pathway (see Section 2.4.4).
- Have a good understanding of possible chemical processes from long-term disposal and storage.

7.5 What kinds of waste treatment are common?

The EU Waste Directive [135] defines waste treatment as recovery or disposal operations, including preparation prior to recovery or disposal. It encompasses any operation that changes the characteristics of waste to reduce its volume, reduce its hazardous nature, facilitate handling, or enhance recovery. Waste treatment is broken down into five types:

- recovery,
- incineration with energy recovery,
- other incineration,
- disposal on land, and
- landfilling.

To avoid misunderstandings, hereinafter, in this section, the term treatment is used in this meaning.

As discussed previously in this book, NORM is mostly unintentionally present in industrial installations and processes and is usually unavoidable without a crucial modification to the technological process in use. If NORM is present in industry waste and/or discharges, such waste treatment can lead to exposure of workers, including workers in disposal or recovery facilities, exposure of members of the public, and exposure of the environment, including non-human biota. Moreover, even if the concentration of the NOR in the materials processed and handled in installations (feedstock or raw materials) is below any local legal limits, NOR might accumulate in the technical process residues. It must often be considered for further use, or, if impossible, classified as any type of waste, just to avoid unnecessary/uncontrolled exposure to ionizing radiation. It is especially important in any case of NORM release into the environment, where proper identification of the final NOR fate is crucial to take a proper decision about disposal or recovery option (Figure 7-3).

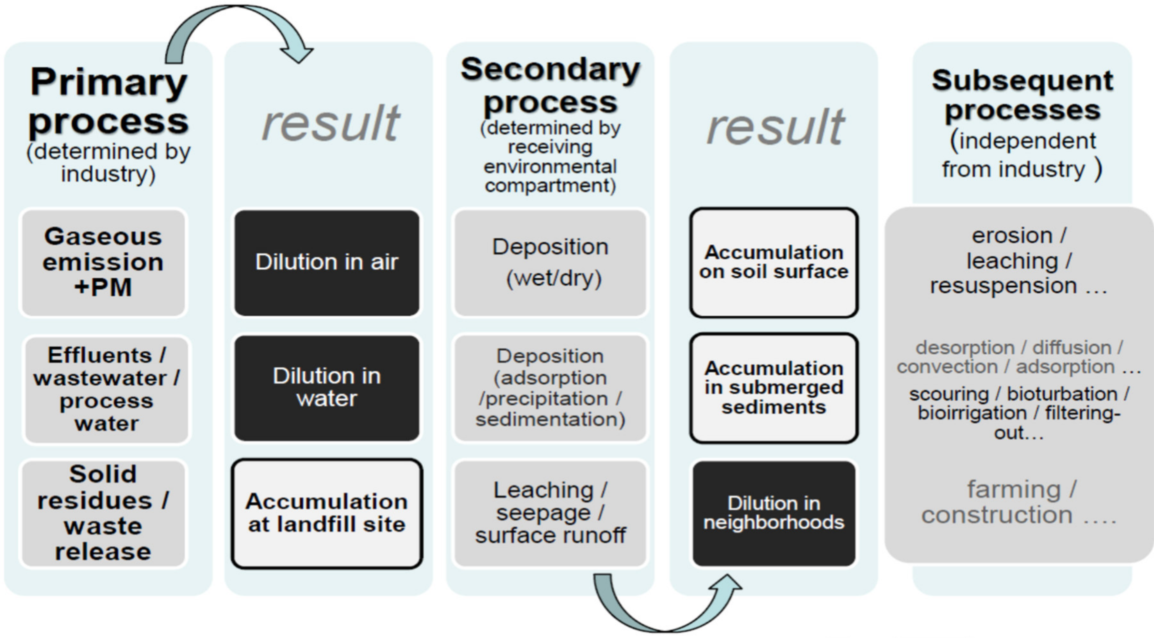

FIGURE 7-3 PROCESS UNDERSTANDING AND IDENTIFICATION OF KEY PROCESSES LEADING TO NOR ACCUMULATION AFTER RELEASE

Therefore, whenever choices need to be made to determine treatment possibilities, it is important to assess all available options and to determine which option is preferred based on all potential exposure to ionizing radiation routes as well as other waste properties determined by physical and chemical properties, including the presence of other contaminants.

It must be underlined that NOR is scarcely the only hazardous aspect of solid waste or effluents. Whenever choices on treatment routes are to be made, all hazardous aspects should be taken into account, and, to ensure a holistic approach, non-radiological hazard aspects such as the total amount of waste to be managed and related supported activities, such as transport, necessary either space or volume up to global warming potential or the carbon dioxide footprint, should also be considered.

Other determinative aspects in NORM waste processes are created by local legislation. Although certain NORM waste treatment options might be preferred based on exposure, environmental, and sustainability criteria, it is possible that they're not allowed by local authorities. There is an important task for regulators to identify and attempt to remove these barriers in legislation to enable the industry to process NORM waste as optimally as possible. One legislative barrier could be removed if the clearance of NORM waste would be allowed in a flexible manner that focuses on dose instead of generic activity concentrations (see examples in Section 7.7.9).

A general requirement for any kind of NORM waste treatment should be record-keeping. Ordinary waste ordinance usually requires that the waste producer describe the properties and composition of any waste, and this information accompanies the waste on its future way; the information of radionuclide content should be part of this waste description in case of NORM.

Some materials where specifically uranium or thorium are significantly accumulated during industrial processing (regardless of the concentrations of the daughter nuclides) may become materials with additional requirements from safeguards if nuclear materials are formed. An example of such material is the ion-exchange cartridge used to remove uranium from water from an underground source.

The recent outcomes of the EURATOM RadoNorm project [142] provide an overview of existing options for NORM waste treatment, as well as suggestions for improving the current situation [143].

7.6 Case example: Formation water

Formation water, co-produced with oil and natural gas or coal (commonly referred to as 'produced water'), contains NOR. When released into any environmental compartment, these NOR can cause direct environmental impacts. Additionally, changes in pressure, temperature, or chemical conditions during exploitation can cause dissolved NOR in the water to precipitate. This precipitation forms scales or sediments rich in NOR, which can contaminate installations or receiving environmental compartments, directly exposing workers or members of the public and non-human biota, respectively (Figure 7-4).

FIGURE 7-4 POSSIBLE EFFECTS CAUSED BY THE DISCHARGE OF MINE WATER INTO THE ENVIRONMENT.

To avoid this, scale inhibitors are used to reduce NOR precipitation in produced water systems. Since NOR precipitation leads to scales or sediments rich in NOR, their reduction can be considered a form of waste prevention. However, it is important to note that the total activity of NOR within the process is unaffected by the use of scale inhibitors. When NOR are not deposited in scales, they are instead present in other effluents, which, if disposed of into surface waters, may result in greater environmental impact compared to disposal in scales or sediments.

Produced waters are also an example where purification from NOR can be applied. This usually applies as preparation before disposal; therefore, it can be somehow accounted as a method of reducing the amount of waste requiring special treatment. The technical solutions applied are mainly based on forced co-precipitation of radium-barium sulfate. In certain cases, evaporation is employed as a method for purification; however, this process typically demands high energy input and is therefore most feasible in climates that support evaporation without substantial energy consumption. Regardless of the method applied, crucial problems arise, such as in the natural process of scale formation and in residues created after purification due to the high radium content. Addressing the issues associated with these residues is critical for ensuring safe and effective application of produced water purification.

Regardless of scales or sediments creation, produced waters are often re-injected into the oil and gas reservoirs from which they originated. While re-injection could be viewed as disposal of NOR, the concentration and volumes of NOR in both the produced waters and oil and gas reservoirs remain largely unchanged. Because these activities are conducted as part of overall production processes, these approaches may be considered as a form of waste prevention. It results in limiting the total amount of produced water that needs to be treated.

Decision-making in this context can involve a compromise between environmental impact from produced water disposal and occupational exposure for workers involved in system maintenance or scale treatment processes, as well as consideration of the ease and cost associated with disposal of contaminated scales or sediments.

7.7 Waste management

7.7.1 What is NORM waste? – The European experience

Waste is defined in the EU Waste Framework Directive 2008/98/EC [135], as "*Any substance, material or object which the holder discards or intends or is required to discard.*"

The European Waste Directive [135] does not address radioactivity as a property of waste, leading to ambiguities and challenges in practical implementation, particularly in cases where the waste contains more than negligible amounts of natural radionuclides. Surveys carried out proved that national legislative and regulatory frameworks for the regulation of NORM in the EU are developed in accordance with the EU BSS [144], however, it is often expressed that the need for the development of improved and more consistent operational and management procedures for overall NORM waste still exists [145]. A variety of approaches to the management of NORM waste in European countries, with a focus on NORM waste disposal, was also provided by the recent study done by the IRPA TG NORM [146].

The European Waste Directive excludes (among others) radioactive waste classified under a national legal framework and effluents, making them subject to separate regulations. This legal categorization opens different approaches for the regulators and various interpretations of the regulations in practice. For instance, several national regulations in Europe treat NORM waste as a distinct category from radioactive waste (e.g., Austria, Czech Republic, Finland, Germany, Hungary, Ireland, Italy, Luxembourg, Romania, and Switzerland). To better distinguish from waste, the term **residue** that was introduced in the former EC Directive 29/96/EURATOM [147], is further used. Other countries like Norway (and Denmark, France, Lithuania, the Netherlands, Poland, Slovenia, Sweden, and the UK [148] consider NORM waste as part of radioactive waste. A third way is performed in Belgium and Spain. NORM waste is regulated as radioactive waste in these countries when management through conventional waste management routes would result in doses to workers and/or the public above certain dose thresholds or exceeding activity concentration values consistent with such thresholds.

To date, there remains no universally accepted legal definition of "NORM residues". Instead, the IAEA Glossary [4] defines "NORM residue" as "*material that remains from a process and comprises or is contaminated by NORM*," which is pertinent to these types of residues. Many such residues possess valuable properties and may be repurposed; this is highlighted in the IAEA document [149], which broadens the definition to "*a material generated in production that can serve a beneficial use and whose use is authorized by the relevant regulatory authorities*." However, when these materials become unwanted or unusable, they must be classified as waste in accordance with conventional waste management regulations. Consequently, it is logical to conclude that the term "NORM waste" effectively addresses this categorization concern.

7.7.2 Waste hierarchy

To achieve optimal use of materials, maximize benefits from waste by-products, and minimize waste generation, the waste hierarchy is a basic principle in conventional waste management. As the goals of NORM waste management are similar to, or even equal to, those of conventional waste management, the waste hierarchy should be used in decision-making processes involving NORM as well. In the context of the holistic approach, it is important that all aspects, including communication with the public, are considered.

Generally, waste management must consider two sides: waste generation ("upstream") and treatment of generated waste. In the UN Global Waste Management Outlook 2024 [150], the following "waste hierarchy" is defined:

- UPSTREAM Prevent - Reduce - Reuse
- DOWNSTREAM Recycle - Recover energy, heat and control emissions - Dispose

The Figure 7-5 gives a schematic overview of the waste hierarchy introduced by the EU directive on waste. This hierarchy is also considered in the IAEA Publication regarding management of NORM waste [138]. Through waste prevention, waste minimization, the reuse of materials, recycling, and finally recovery, the volumes of waste that need to be disposed of are reduced. Each step in the waste hierarchy is elaborated in the following paragraphs.

FIGURE 7-5 WASTE HIERARCHY ACCORDING TO THE EU WASTE FRAMEWORK DIRECTIVE

(SOURCE of this figure: …)

Waste prevention is the priority, followed by reuse (i.e., products or their parts that are not waste are used again for the same purpose) or recycling, i.e., waste is reprocessed into products, materials, or substances for the original or other purposes. Reuse and recycling are the core elements of the circular economy.

Lower levels of the waste hierarchy start with energy recovery, including reprocessing waste into materials to be used as fuel, and other recovery where waste serves a useful purpose by replacing other materials that would otherwise be used for a specific purpose, and, if none of these options is feasible, disposal.

Increasingly, waste producers are becoming aware (or are being made aware by regulators) of the UN Sustainable Development Goals, and a desire to move from a linear economy to a circular economy, placing particular emphasis on the re-use and recycling aspects of the waste hierarchy.

7.7.3 Waste prevention and minimization

The first option considered, where possible, is to avoid feedstocks with high NOR content or mix them with other materials to mitigate anticipated NOR contamination issues. This requires a careful cost-benefit analysis, weighing the value of the product against the costs associated with all activities necessary and the potential loss of overall process efficiency ("holistic approach").

A good example is fertilizer and phosphoric acid production, where the choice between magmatic (apatite) and sedimentary phosphate rock can be considered. Due to its magmatic origin, apatite usually contains less NOR; other factors, such as overall availability, market price, and processing difficulties, ultimately determine the decision. Considering all facts, sedimentary phosphate rock is the most feasible and economical raw material used for fertilizer and phosphoric acid production.

Similar holds for coal combustion. However, coal combustion reduces feedstock mass by converting solid carbon into gaseous CO_2, resulting in NOR accumulating in ash (cf. Section 3.10.4). Thus, elevated NOR content in feedstock is an essential, but not necessary, condition leading to their significant accumulation.

Waste minimization might include using specific materials for the inner surfaces of pipelines transporting groundwater or processing mineralized water, thereby reducing the formation of NOR-rich incrustations.

Therefore, careful evaluation of each process feature is needed to minimize NORM waste generation. For example, because the concentration factor after combustion depends on the carbon-ash ratio in raw coal, to some extent, it is possible to control NOR activity concentration in ash by selecting combusted coal.

In general, switching from one raw material to another one, not so rich with natural radioactivity, is very limited as the content of NOR or the association of a specific raw material with NOR under either geological or hydrogeological conditions is a primordial property of a resource, and the availability of alternative resources is limited. For instance, natural oil and gas are usually associated with radium-rich formation waters, while many non-ferrous metal ores (Sn, Cu, V, Mo, etc.) may be associated with uranium [141]. A particular case is REE ores, which are mixtures of isomorphous non-radioactive and radioactive minerals, e.g., cheralite, huttonite, and monazite. In such cases, to minimize the amount of waste or to avoid NOR accumulation, modification of a technological process should be considered. For instance, acidification of feedstock slurries can extract specific radionuclides, resulting in their concentration in reaction vessels or further downstream in the treatment process.

Some examples of waste prevention and minimization are discussed below.

7.7.4 Solid waste mixing

Mixing NORM residues to reduce the activity concentration is frequently believed to be prohibited under the legal dilution ban. However, this interpretation is a typical "storytelling" occurring in practice. Mixing is prohibited unless specifically intended to reduce the activity concentration of waste below exemption or clearance values, without the authorities' approval.

Moreover, the normal blending of NORM as a feed material in an industrial process is not covered in the dilution ban. E.g., zirconium oxide that is added with other components to make glazed ceramics is not a waste, and the process is not considered a dilution. If, however, waste materials are recycled and added to a production process, the question of whether this requires approval is open to case-specific interpretation (see below).

Generally, the mixing of residues for

- mechanical stabilization (solidification with concrete),
- reduction of potential leachability by chemical treatments,
- avoiding dangerous goods transport by establishing an activity concentration complying with the 10-fold exemption value for NORM according to the dangerous goods regulations (see Chapter 8)

is not covered by the mixing ban. It needs (usually) no permit if the mixed activity concentrations remain above the legal exemption values for radiation protection.

Moreover, in recent years, mixing has been recognized as a legitimate and desirable option for minimizing the quantity of NORM waste requiring special treatment. However, a general legal requirement is that dilution of residues from NORM involving industries requires the review and approval of the competent authority.

Recent EU BSS [151] provides a justification of NORM mixing, as a general method to lower NOR activity concentration under specific conditions approved by a decision of Member States, especially dilution for recycling, when this is considered to be the optimal solution. The general approach for this route is first to see whether the NORM residue can be processed into a useful product (considering technical, economic, and environmental aspects) and, second, to conduct an overall safety assessment of the radiological implications for a given process and application, to see whether any significant consequence for health and the environment could occur. Significant consequences may occur during the processing of the residue as well as during the whole life cycle of the product. In the latter case, e.g. the leachability of radionuclides from a product of concern, subsequent contamination levels and exposure, eventually doses to either human or biota are aspects which have to be taken into consideration, following the scheme depicted in the Figure 7-3. When all of these aspects are shown to meet the corresponding criteria set, the technical development and processing of the NORM residue can proceed [152].

It is worth noting that reuse or recycling of NORM in the construction industry, where relevant rules and criteria are legally established, or other possible uses, e.g., as phosphogypsum to improve soil properties, can be considered as a case of NORM blending.

In case of solid NORM preparation based on waste mixing or better blending, as the expected result is an inseparable, uniform composition of mixed components, it strongly depends on the available materials/waste to be mixed and the existing technical infrastructure. The dilution of NORM waste can be considered as the opposite process to NORM accumulation. Therefore, blending of waste created in the frame of one technological process neither changes nor introduces external impurities into the process, which provides a rationale for such a solution. On the other hand, the development of an infrastructure, especially for mixing NORM residues, is usually not economically justified. That is why each case must be considered individually.

Any kind of mining provides most options for mixing, as there are usually different waste streams that differ significantly in total abundance and radionuclide activity concentration. Moreover, a whole production process applied usually creates many technical opportunities for effective mixing, assuring appropriate radionuclides dilution without significant changes and investments. An approach based on the dilution of radium-rich sediments from mine waters was tested in a Polish coal mine [153].

7.7.5 Reuse of NORM

Reuse means to use material again. While the IAEA [4] understands the term broadly, including "*conventional reuse, in which an item is used again to perform the same functions, and reuse in which an item is used again to perform a different function*", the EU Waste Directive defines reuse as an operation applicable only to products or components that are not waste and limits it to use for the same purpose for which they were conceived.

One example of reuse is the AZS (Alumina-Zirconia-Silica) refractory material removed during the dismantling of smelting units. Undamaged bricks of this material can be reused to line a smelting unit with refractory bricks [154].

One option, not restricted by NORM content, involves incorporating certain residues back into the same process by adding them to the feedstock. This approach is feasible when these residues still contain elements desirable during processing or possess properties that can beneficially influence the operation. In some countries (Germany, #where else?), the reuse of materials within the same process is excluded from the definition of residues by law.

Notable examples include dust from pyrometallurgical processes. Blast furnace dust of pig iron production contains (besides Pb-210) enhanced zinc and lead concentrations. Such dust can be used as a feed material in zinc and lead metallurgy.

Another example is dust from primary tin smelting, which can be used for its original purpose or in lead sourcing [155], as well as kiln dust collected during cement production (CKD – cement kiln dust) [156].

Often, however, special treatment is required to enable the reuse of NOR residue; for example, electrodynamic fragmentation applied to spent refractories can yield high-purity regenerates suitable for manufacturing new refractory products without compromising refractoriness or strength [157]. Beyond the direct benefits from a radiation protection perspective, these solutions also reduce raw material consumption, energy use, and CO_2 emissions. Additional options include utilizing NORM to support main technological activities throughout the production process. For instance, produced water is sometimes employed in underground mines as a carrier in backfilling operations to mitigate surface subsidence, while various NORM residues, such as coal ash, are directly used as backfill materials or CKD that can replace cement in mine backfill (as well as in concrete, to some extent) to get the required strength, reducing binder cost.

More options for NORM residue reuse exist outside the primary process, where they are used for other purposes, without significantly changing their original form or aggregate state. Typical examples are listed in the Table 7-2 but not limited to.

TABLE 7-2: TYPICAL OPTIONS FOR NORM RESIDUE REUSE

Industry	NORM Source	Reuse /Application
Fertilizers/phosphoric acid production	Phosphogypsum	Soil conditioners, building materials, roads construction
Energy generation	Coal combustion products (CCP)	Cement, concrete, backfill material, REE sourcing,
Mining	Mine water, tailings	Coal beneficiation, backfilling process, backfill material
Ceramics	Zircon sands	Tiles, refractories

The special cases are installation parts and equipment, such as pumps and valves, that are contaminated with NORM. When these NOR-contaminated items are in a good state but become redundant, reuse should be considered. Reuse as is (without prior decontamination) should be preferred. If the presence of NORM interferes with the proper functioning of the equipment or maintenance is required, prior decontamination may be necessary.

It needs to be said that the presence of NOR often limits reuse options, regardless of the technical obstacles it causes. In many cases, the presence of NOR requires registration or licensing, and when these are not already in place, this will cause a barrier. In some cases, decontamination of the equipment can resolve this issue, but it might not be cost-effective or practicable. Furthermore, the decontamination techniques used can be abrasive or destructive, leading to defects. Additionally, the solid residues or liquid waste generated following decontamination could be problematic and expensive to dispose of. If a decontamination station is set up, it is necessary to ensure adequate protection for its operators, including radiation protection requirements.

Special case: France

A country that has strictly prohibited the addition of radionuclides and the use of "SRON" in consumer goods and construction products (Article R.1333-2 of the CSP), is France. The use of SRON in the manufacture of consumer goods, food, or animal feed is prohibited. The addition of SRON to construction products is also prohibited.

SRON is defined as a material where the activity concentration of radionuclides in uranium or thorium decay chains may exceed 1 Bq/g, or the activity concentration of ^{40}K may exceed 10 Bq/g.

This restriction also applies to products imported into the European Union from a third country to which radionuclides have been added, as well as to the distribution and use of such products.

Exemptions from these prohibitions may be granted if they are justified by the benefits they provide in light of the health risks they may pose. However, foodstuffs, animal feed, materials intended to come into contact with foodstuffs and water intended for human consumption, toys, jewelry, and cosmetics are excluded from this exemption regime.

In 2022, this restriction framework was amended by introducing, into the Public Health Code, a new exemption regime for the use of very low-activity metallic substances originating from a facility where a nuclear activity is currently being carried out or has been carried out in the past, provided that these substances have first undergone a recovery operation at an authorized facility. Within this framework, clearance thresholds, corresponding to the exemption values defined in the authorization regime applicable to nuclear activities, have been introduced. Since the products resulting from the recovery process are no longer considered radioactive substances, they no longer require radiation protection controls.

7.7.6 Recycling

Recycling means „*the process of converting waste materials into new products.*“ (IAEA definition). The EU Waste Directive is more specific and defines recycling as *any recovery operation by which waste materials are reprocessed into products, materials, or substances, whether for the original or other purpose; whereas energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations are not considered as recycling.*

NORM residues released during industrial processes may also have value for other processes. Fly ash can be used in concrete, cement, or cementitious fiber board production; phosphogypsum can be used in fertilizer production; and slag can be used in (road) construction. Depending on the specific process, actions taken can be considered as direct reuse, reuse after preparation, or recycling. Following the appropriate definition, for instance, applying ash as a soil conditioner should be considered a direct reuse, while using the same coal ash as an additive to cement should be considered recycling, since the new product emerges as the final result.

To illustrate recycling, contaminated scrap is a good illustrative example. When installation parts and equipment become redundant or obsolete, and reuse is not foreseen, recycling of material should be considered. Although options for recycling metal and plastics are readily available, the presence of NORM is, in most cases, not accepted. Usually not because of any (potential) exposure risk, but because of regulatory requirements or perception and reputational issues. Smelting companies will often not accept NORM-contaminated metal scrap, even if the average radionuclide concentration of the scrap is lower than the concentration in ores that the same smelting company is using.

In most cases, NORM-contaminated scrap must be decontaminated to enable further recycling. However, it may be possible that decontamination does not have to remove all detectable contamination, and that scrap with relatively low levels of residual fixed surface contamination can be recycled. For example (and subject to regulatory approval), relatively low levels of fixed surface contamination may be acceptable, following consideration of the thickness of material underlying the surface contamination, and calculation of a bulk activity concentration of the whole item. If it can be demonstrated that this bulk activity concentration meets the appropriate regulatory limits, the item could be freely released for recycling. However, care must be taken as any residual low-level surface contamination could potentially trigger sensitive detection equipment further downstream in the metals recycling chain.

Given that recycling occurs outside the mother process that leads to NORM creation, it is often more difficult than direct reuse, again due to regulatory requirements or reputational and perception issues. This could be overcome through proper communication on the NORM topic in the country, and cooperation of the regulatory authority and waste producers.

7.7.7 Valuable elements/minerals recovery

NORM residues are typically mixtures of various impurities removed from feedstock during processing to obtain the desired product. These mixtures are often considered useless and can be hazardous, not only because of their NOR content. However, technological processes that concentrate NOR in residues may also serve as pretreatment steps, resulting in the accumulation of elements or minerals that could be valuable if separated. Therefore, NORM residue can replace natural raw materials usually used for the sourcing of specific minerals or elements. For example, coal ash or red mud may contain enough rare earth elements for extraction. Sometimes, extracting valuable substances from NORM residues may create a win-win situation: the recovered material has commercial value, and the leftover residue is improved for other uses. For instance, chlorine-rich cement kiln dust (CKD) can be washed and processed to extract high-purity potassium chloride (KCl) for fertilizer, while the cleaned residue can be returned to the kiln without causing further chlorine pollution in cement production [158].

Such situations become extremely interesting for NORM involving industries when NOR become subject of interest. Recent advances in nuclear medicine highlight the significance of radium, especially for Targeted Alpha Therapy (TAT), which uses short-lived alpha-emitting radionuclides obtained via Ra-226 transmutation. With current TAT isotope production relying on legacy Ra-226, increasing demand necessitates new Ra-226 sources. As discussed in previous sections, radium is found in produced water from fossil fuel extraction, leading to environmental challenges despite purification efforts that generate radioactive waste. Utilizing both purified materials and residues for Ra-226 extraction and TAT radionuclide production demonstrates the potential for zero-waste technology and creates added value from previously problematic NORM residues (Figure 7-6).

Another example of reuse in the medical field is the production of radiopharmaceuticals based on Pb-212 (under development in France, already in production in the U.S.).

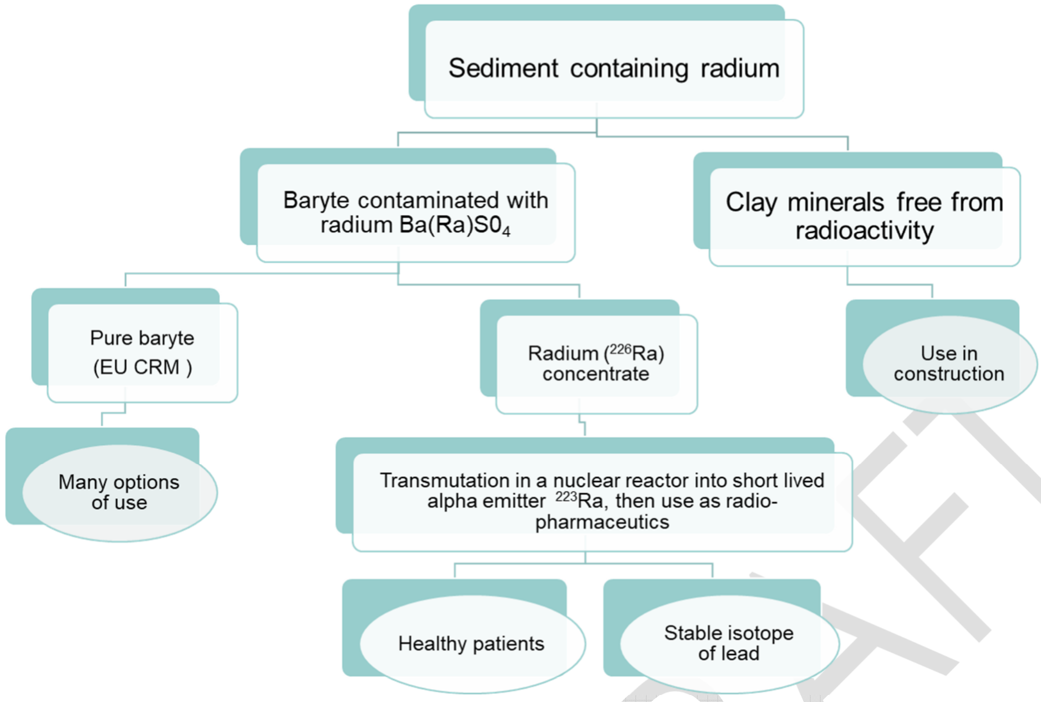

FIGURE 7-6. AN EXAMPLE OF THE OVERALL CONCEPT OF THE TREATMENT OF RADIUM RICH SEDIMENTS EMERGING FROM MINING ACTIVITY

7.7.8 Energy recovery

If NORM cannot be reused or recycled and is eligible for energy recovery through incineration (or co-incineration), this option should be assessed. An example would be the incineration of contaminated oil and sludges from the oil and gas industry if they have a suitable calorific value. Similarly, NORM-contaminated waters could be used for process/temperature control during the injection of materials into the chamber during incineration. Not only should heat recovery in incinerators be considered, but some NORM waste can be used as an alternative fuel in clinker ovens. In such cases, NORM waste can benefit cement production, such as reduced energy needs and lower CO_2 emissions; however, their contribution must be included in the overall balance of NORM across the entire cement production process. It should be noted that alternative fuels can introduce additional contaminants into the process as well.

Incineration typically involves significant volume reduction, and care is required, given that radionuclides can concentrate in bottom ash and fly ash, which may themselves become problematic not only in terms of NOR-contaminated wastes. The burn schedules of an incinerator can, however, be programmed in such a way as to avoid such issues by considering the activity of the feedstock and estimating the activity within the waste products as a result of the volume reduction associated with the process.

Given all possible options of NORM residue recovery in the context of current circular economy requirements, it is necessary to consider the possibility that NOR may re-enter circulation as part of reuse, via recycling or recovery of NORM residue, for example, as components of certain products, potentially increasing exposure to natural radionuclides for users of such products without any possibility to control them. This process is currently regulated at the European level only for certain types of construction products.

7.7.9 Disposal

Disposal is the ultimate, least favored option in the waste hierarchy and should be used only if the previous steps are not feasible.

In the IAEA Glossary [4], disposal is defined as "*Emplacement of waste in an appropriate facility without the intention of retrieval.*" The IAEA added that in some states, the term disposal includes discharges of effluents into the environment or incineration of waste or the transfer of waste between operators.

In this handbook, we use the term disposal as defined by the IAEA. Incineration may be an intermediate step that uses the energy content of the waste, but it is not considered disposal in a narrow sense.

Discharges are briefly discussed in Section 7.#.

Whenever NORM is classified as waste, whether volume reduction through incineration (similar to Section 7.7.7 but without energy recovery, pyrolysis, or other means is feasible as discussed in the section 7.7.5. Depending on the effects of preparation and the final properties, NORM waste can be disposed of in conventional landfills, hazardous waste landfills, specific NORM landfills, or depositories for radioactive waste. Although in most cases the choice of depository will be determined by national legal requirements, it should be noted that the type of depository needed to hold NORM waste should be assessed based on the waste characterization (not only the radioactivity contents but also any other physical, chemical and hazardous aspects), the relative volume of the waste (is it only NORM waste or is it mixed with different types of waste) and the environmental barriers provided by the depository.

As underlined in Section 7.2, waste currently referred to as NORM waste has not appeared suddenly and has often existed since a relevant industry was set into operation, and is currently managed within a well-organized system developed under relevant EU directives and applied consistently across all EU Member States. The problem of NORM is relatively new, and in practice, existing options for such waste disposal must be evaluated from a radiation protection perspective. The biological effects of ionizing radiation — including carcinogenicity, mutagenicity, and reproductive toxicity — are analogous to those addressed by hazardous waste properties HP7, HP10, and HP11. However, radioactivity is not classified as a hazardous property of waste. NORM waste must therefore be assessed for hazardous properties on the basis of its chemical properties, as any other waste. Therefore, often only additional exposure pathways, such as external gamma irradiation, must be considered when evaluating an existing disposal option for NORM waste disposal.

Through choosing the proper type of depository, it should be ensured that exposure to the public is kept below (inter-) national limits, via radiological risk assessment and consideration of the potential post-disposal transport of NOR through the environment. Decision criteria applied are expressed as NOR activity concentration or effective dose and usually are based EU BSS clearance and exemption levels.

Two examples of different national regulations

In France, the choice of the disposal facility for waste containing NORM / SRON (Cf. Chapter 11) is based on the NOR activity concentrations (Table 7-3). In Germany, the NORM waste covered by the law is defined in a Positive List (Annex 1 of the RP Act). The regulations distinguish between the general term "material", which does not specify regulatory status; "residues", which are materials that should be discarded (are waste!) but need notification only if the amount exceeds 2000 Mg/a; and "Residues requiring monitoring". The latter are radioactive substances under the law and require approval from the authority before disposal (Table 7-4). However, category of landfill mainly depends on the chemical properties, and radioactivity is subject to site specific decision of a relevant authority, if considered at all.

TABLE 7-3: WASTE CLASSIFICATION IN FRANCE

	Inert waste landfill	Non-hazardous waste landfill	Hazardous waste landfill	radioactive waste disposal facility
NORM < 1 Bq/g	X	X	X	X
1 Bq/g < SRON < 20 Bq/g		X (with radiological environmental monitoring)	X (with radiological environmental monitoring)	X
20 Bq/g < SRON				X

The German regulatory system has two steps

- First step is the graded approach, how NORM residues are exempted or classified as monitored residues (Table 7-4).
- Second step is the clearance that makes NORM waste to conventional waste and enables disposal on landfills.

TABLE 7-4: GERMAN REGULATORY SYSTEM FOR NORM-WASTE: CATEGORIZATION AND REGULATORY STATUS OF RESIDUES ACCORDING TO ANNEX 5 RPO

AC	AC refers to …	Category	Regulatory status
< 0.2 Bq/g	Each decay series radionuclide	(Material)	Outside of scope
< 1 Bq/g	Sum activity (Specific enhancements for Pb-210, Po-210)	Residues	Notification of large amounts (> 2000 Mg)
> 1 Bq/g		Residues requiring monitoring	Notification. Disposal needs approval. Approval based on activity concentrations* is possible.
< 10 Bq/g			
< 50 Bq/g			
> 50 Bq/g			Approval for disposal based on dose estimation is required

Explanations / Notes: AC – Activity concentration; * - up to 50 Bq/g only for hazardous waste landfills, otherwise 10 Bq/g.

TABLE 7-5: GERMAN REGULATORY SYSTEM FOR CLEARANCE OF MONITORED RESIDUES ACCORDING TO ANNEX 6 AND ANNEX 7 RPO

AC	AC refers to …	Comment
(unlimited)		The prior criterion is 1 mSv in a year. Compliance must be demonstrated with realistic assumptions (Annex 6 RPO)

0.05 Bq/g	Activity concentration averaged over the total annual mass of waste	for landfills with an area of more than 15 hectares
0.1 Bq/g		for landfills with an area of up to 15 hectares
1 Bq/g		regardless of the landfill area for landfills where groundwater contamination can be ruled out due to specific site conditions, and
5 Bq/g		for underground disposal

Explanations / Notes: AC – Activity concentration; * - up to 50 Bq/g only for hazardous waste landfills, otherwise 10 Bq/g.

7.7.10 NORM-waste landfilling

Landfilling has been established as a principal route for industrial waste management. In accordance with Section 7.3.5, such landfills are regulated by the EU Waste Framework Directive, which, under Article 2 paragraph 1d, excludes "radioactive waste" from its scope. Consequently, materials classified as "radioactive" are excluded from standard waste management procedures. Specific facilities for landfilling NORM waste have been authorized in certain jurisdictions, such as France and the Netherlands.

A dedicated repository for NORM waste has been commissioned in Norway. Nevertheless, widespread practice, particularly for substantial volumes with moderate activity concentrations, involves landfilling. For NORM waste containing significant organic fractions, incineration prior to landfilling is adopted.

Landfilling at facilities designated for conventional waste necessitates prior release from radiation protection oversight. National regulatory frameworks governing the interface between radiation protection and waste legislation are, therefore, critical to the practical landfilling of NORM waste.

Survey data indicate substantial national variation in the approach to landfilling of NORM waste. While some countries have implemented robust systems enabling the release of NORM waste from radiation protection and subsequent landfilling as conventional waste, in others, regulatory provisions classifying NORM waste as radioactive waste often remain ineffective in practice.

Key practices identified as effective in the landfilling of NORM waste include:

- Efficient landfilling is achieved when all stakeholders apply legal requirements pragmatically.
- In Germany, generic dose assessments for exposure pathways have been established, setting a maximum activity concentration of 10 Bq/g for U-238 and Th-232 series nuclides. Compliance allows for release from regulatory control without additional calculations.
- Experience in Germany demonstrates that landfilling has not resulted in annual doses exceeding 1 mSv for landfill workers.
- Mandatory monitoring ensures that exposures remain below 1 mSv/year. Site-specific modeling is required if concentrations exceed 10 Bq/g, and compliance is generally achieved.

- Monitoring, though not dose-reducing, provides assurance; studies in Belgium found no significant difference in groundwater quality between NORM landfills and other sites.
- Effective communication between radiation protection and waste management authorities facilitates realistic risk assessment and appropriate regulatory focus.
- Landfilling is considered complete and regulatory release valid when transport and burial are conducted as per the approved plan, ensuring adherence to safety criteria.

Barriers to effective landfilling of NORM waste include:

- Misinterpretation of waste legislation by landfill operators, particularly regarding the exclusion of radioactive waste, and lack of a dedicated NORM category in the European Waste Catalog. Training is recommended for all stakeholders.
- Classification of NORM waste as hazardous restricts landfilling to limited facilities, resulting in dependence on a few operators and potential cost escalation.
- Restrictive approval procedures, including the mandatory application of regulatory requirements above exemption values, regardless of exposure magnitude or likelihood, impede landfilling.
- Demonstration of compliance with dose criteria is time-intensive and may not be proportionate to the actual risk, thus hindering landfilling.

Enhanced understanding of NORM waste origins, properties, and landfilling options is essential for efficient management. Studies conducted across Europe and industry involvement in data collection have facilitated the development of effective management strategies, although commercial confidentiality remains a concern. Knowledge sharing among countries with similar industrial profiles is encouraged.

Industry associations and regulatory authorities are advised to disseminate concise, factual information to promote evidence-based approaches to NORM waste landfilling.

Despite regulatory efforts, securing landfilling routes remains challenging due to operator reluctance and diminishing landfill capacity. While regulatory frameworks guarantee release from control, acceptance for landfilling is subject to the discretion of waste management entities.

State-owned landfills, mandated to accept released NORM waste, may offer a solution. However, public perception issues must be managed, and regulatory neutrality in risk assessment is required.

7.8 NORM and Circular Economy

In the following, we provide some real-world examples of NORM and the system of protection and show how sustainability is constrained in practice by the formal application of radiation protection criteria in some circumstances. A broader discussion on the relation of NORM and sustainability was published in [159].

NORM-contaminated scrap

In industrial plants where NORM is processed, waste metal components are sometimes surface-contaminated with NORM and are emerging during maintenance and repair. Even larger quantities of contaminated scrap are produced when plants are dismantled at the end of the operation.

Scrap is a valuable resource, and the recycling of ferrous scrap is a well-established process in a circular economy. However, this process is often hindered by radioactivity. Owing to the melting of industrial radiation sources and the associated economic damage, a culture has been established in the steel industry that is geared towards the complete exclusion of radioactivity. Starting in the scrap trade, portal radiation measuring systems are used to identify and control radioactivity. These systems use large-area detectors to register count rates, and are often set such that an alarm is triggered if a level twice the background value is exceeded. Scraps that trigger radiation alarms are not accepted for further processing.

This procedure is implemented regardless of whether the radioactivity in question required monitoring according to the radiation protection criteria. As this procedure does not run counter to the legal requirements, but even imposes far stricter restrictions than required by law through agreements under commercial law, it is difficult to raise objections to it on the radiation protection side. Although it is clear that the radionuclides of uranium, thorium, and radium contained in NORM are strongly diluted in the slag in the melt, and Pb-210 and Po-210 evaporate and are collected as filter dust; the associated radiological consequences are not an issue for the steel industry.

Another pathway that results in the disposal of ferrous metal instead of recycling is the formal application of clearance criteria for surface contamination by authorities. The following example illustrates this problem.

As a result, large quantities of ferrous scrap are dumped instead of recycled, even though a radiological risk assessment would show that the risks are low.

Pb-210 contaminated lead

The presence of Pb-210 in metallic lead has long been known. (Heusser 1995) describes Pb-210 concentrations of less than detection limit up to 2.5 Bq/g in metallic lead and values up to 50 Bq/g in solder. Low-activity lead, in particular, as required for shielding low-level measuring stations, is offered but is significantly more expensive than the lead generally available on the market.

Pb-210 enters smelted lead because lead ores also contain traces of uranium and Pb-210 I also present in the atmospheric air due to radon decay. Pb-210, as an isotope of lead, \ behaves like a chemical element in all the technical processes and is accumulated in the metallic lead.

Practical test results show that common lead ore concentrates have very low Pb-210 contamination of chemical lead. However, lead is also a minor component of tin ores. These ores often have a higher uranium content. Even higher uranium concentrations occur in niobium-tantalum ores. (Antico 2009) studied the metallurgical processing of cassiterite, a co-product of the Pitinga niobium mine in Brazil, for manufacturing tin. In the by-product lead, Pb-210 contamination was determined to (1,600±300) Bq/g. Despite specific uses of this metal would certainly not result in significant exposures, large amounts of lead ingots are stored and are not marketable.

Another material used in lead metallurgy is the waste from other metallurgical processes, where lead is enriched by evaporation at high temperatures. In Table 1, the results of different investigations of lead ore concentrates and waste from metallurgical processes are compiled. To illustrate the origin of the higher levels of Pb-210 in the waste for recovery, Table 2 shows exemplary data on uranium, lead, and Pb-210 in ores and smelter dust. As lead and Pb-210 vaporize during pig iron smelting, they accumulate in smelter dust. Consequently, lead in smelter dust contains a significantly higher activity concentration than that extracted from lead ore.

TABLE 7-6: ACTIVITY CONCENTRATIONS OF PB-210 REFERRED TO THE CHEMICAL LEAD CONTENT IN ORES AND WASTES FOR RECOVERY (UNPUBLISHED RESULTS)

		Lead ore concentrates	Waste for recovery
Min	Bq/g	0.001	0.24
Average	Bq/g	0.041	3.69
Max	Bq/g	0.096	7.48

TABLE 7-7: EXEMPLARY DATA ON PB-210 CONTAMINATION OF METALLIC LEAD WHEN USING DIFFERENT FEEDSTOCKS

Feedstock material	Pb-Content	U-Content	Pb-210	Pb-210 in Pb
	%	ppm	Bq/g	Bq/g
Lead ore concentrates	50	1	0.012	0.024
Iron ore concentrates	0.006	3	0.05	800
Blast furnace dust (pig iron)	1	(*)	5	500

* Not relevant; no activity equilibrium with Pb-210

Because any exceeding the 1 Bq/g exemption limit can lead to restrictions on marketability, the use of metallurgical waste for recovery is voluntarily limited by melting companies. However, from a radiation protection perspective, we wonder whether the radiation risks due to the use of metallic lead at 2 Bq/g or even 20 Bq/g Pb-210 justify such a restriction, in particular because chemical-toxic risks arising from the chemical toxicity of “lead” are also associated with this element. If it is only the "taint of radioactivity" that hinders the use of smelter dust as a resource for lead metal extraction, it is a waste of resources by devaluation, comparable to the taint of "unfashionable" that the clothing industry uses to waste clothing.

Once again, the actual radiological risk assessment would show that the risks are low.

Cross-contaminations in metals

In recent years, we have dealt with practical cases attributable to cross-contamination of metals with radionuclides of natural origin. Both cases, which are described briefly below, were detected by controls using the portal measuring systems.

Titanium metal is typically manufactured from chemically produced titanium dioxide. The thorium content in such titanium dioxide is low, and cross-contamination of metals from chemically pure titanium dioxide is unlikely. Therefore, we suspect that thorium-contaminated titanium metal stems from the recovery of impure raw materials. Such impure raw materials can be by-products or waste from other processes with low titanium content. Similar to the case of lanthanum, the desirable use of low-grade resources results in conflicts with radioactivity and, finally, in disposal instead of recycling.

As lanthanum is also used for pharmaceutical purposes (Treibacher 2025), radioactive contamination is of particular importance. However, lanthanum compounds are also used in less-sensitive applications. This example shows that it is necessary to control use based on a dose-related consideration in order to ensure low-risk use of products in different areas of application.

7.9 Discharges

As activity concentrations in effluents are relatively low and usually below legal limits, their release into an environmental receiver is often not seen as disposal of NORM. Nevertheless, discharges to the environment can contribute to exposure to the public as well as non-human biota, and therefore, NORM content should be taken into account when assessing all waste disposal options. For example, NOR-contaminated marine discharges associated with a phosphate processing facility could lead to the bioaccumulation of certain NOR within seafood, which could result in significant exposures of the public.

7.10 Helpful tips

The key additional issue raised by practitioners in our survey was regarding the transport and transfer of NORM wastes. Since each country has defined its own exemption and clearance system for NORM, the transport and movement of NORM materials (including waste) is problematic. There is a lack of certainty regarding the movement of NORM residues between countries where treatment facilities may exist. While some treatment processes are beneficial (for example, incineration for the generation of heat), due to national restrictions, this may not be possible.

At least some legislation contains a ban on transboundary transport of NORM wastes for disposal in another country, even if they could safely be released from regulatory control based on demonstrated compliance with dose criteria.

Furthermore, it was noted that to some extent, the transport issues are due to NORM materials being excluded from European regulations for conventional waste.

As NORM in industrial processes is usually unavoidable and unintentional, the waste prevention and minimization options are usually limited. As the only source of NOR is raw materials introduced into a process, decision-making should include evaluation of feedstocks in terms of NOR activity concentration.

Routine monitoring of natural radioactivity levels within potential feedstocks is recommended to identify those that may cause issues within the processing facility. This approach can also prevent the inadvertent production of commercial products in which NOR have concentrated to significant levels, thereby minimizing waste associated with products that cannot be marketed due to regulatory limits (e.g. building materials with elevated radium content).

8 Transport of NORM

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8.1 Introduction

The modern economy is based on complex, international supply chains. Some of the goods transported in these chains represent a hazard to the personnel involved, as well as to the general public and the environment. Certain radioactive materials are recognized as dangerous goods, and their transportation is, therefore, subject to control and management.

For the transport of radioactive material, there is a well-established and internationally agreed regulatory approach, which is shown in Figure 8-1.

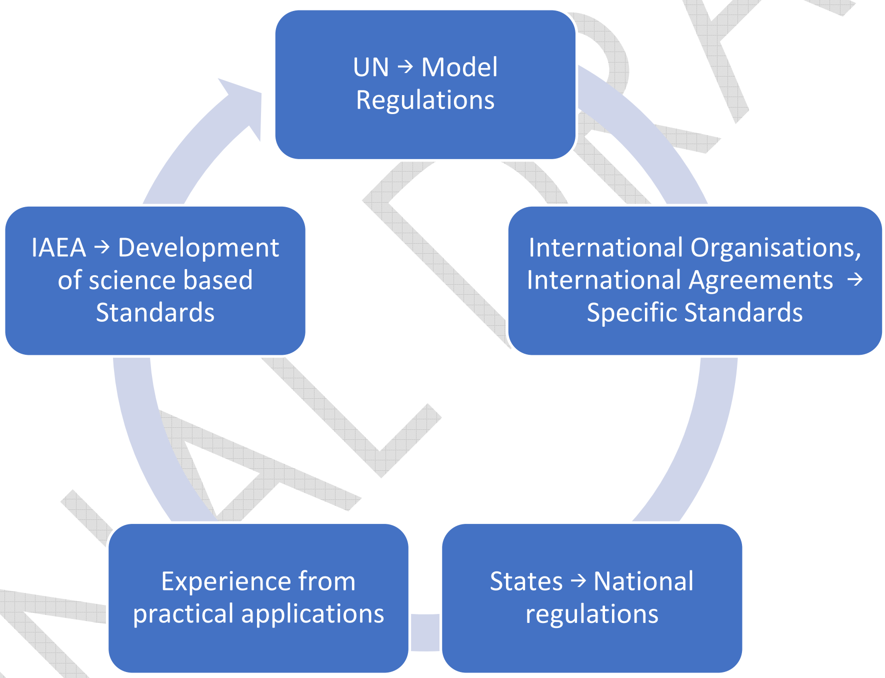


FIGURE 8-1: THE APPROACH TO AND DEVELOPMENT OF STANDARDS AND REGULATIONS FOR THE TRANSPORT OF DANGEROUS GOODS

The United Nations organization responsible for establishing the standards for radiation protection during the transport of radioactive material is the IAEA, which has developed the Regulations for the Safe Transport of Radioactive Materials (also known as the Transport Regulations or SSR-6) [160]. These standards are adopted universally and are included in broader UN advice in Recommendations on the Transport of Dangerous Goods [161]. These UN-Recommendations ("Model Regulations") [162] cover the transport of dangerous goods by all modes of transport except sea-going or inland navigation bulk carriers or tank-vessels. They are not mandatory or legally binding on individual countries until adopted in special international conventions or national legislation.

When writing this handbook in 2025, the UN Model Regulations and consequently many international standards or national laws referred to the 2018 Edition of SSR-6 [160]. In December 2025, the IAEA published the revised 2025 Edition of SSR-6 (Rev. 2) [163], which will be valid during the next few years, and is referred to in this handbook.

The IAEA Transport Regulations form the basis of law in almost every country in the world. They are adopted in worldwide guidance on Transport of Dangerous Goods, such as in:

1. Dangerous Goods Regulations (DGR) of the International Air Transport Association (IATA) for transport by air.
2. The International Maritime Dangerous Goods (IMDG) Code.
3. Maritime Safety Conventions (MSC) of the International Maritime Organization and its sub-organizations (IMO–IMDG/ISM/IBC) for maritime transport.

Regional agreements also incorporate the Transport Regulations, for example:

- European agreement concerning the international carriage of dangerous goods by road (ADR),
- Regulations concerning the International Carriage of Dangerous Goods by Rail ("RID"),
- European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (abbreviation AND).

In the US, the Hazardous Materials Regulations (HMR) are the minimum requirements for the safe transportation of dangerous goods. They describe how dangerous goods are classified, communicated, packaged, labeled, transported, handled, and stowed. The HMR is published in Subchapter C of Title 49 of the Code of Federal Regulations (49 CFR, parts 171-180).

All these standards are consistent with the IAEA Transport Regulations in the way they are organized and in specific requirements.

> **TIP:** If the shipment is transboundary, regulations in all countries on the route must be respected.
>
> **TIP:** The IAEA Transport Regulations usually undergo review every few years. Details must therefore be taken from the current versions of the regulations. Always check the latest IAEA-Standards, no matter your country's regulations.

Although the IAEA Transport Regulations are the international reference document, the national laws are usually based on documents that have integrated the specific regulations into a broader regulatory framework (ADR, RID, etc.). The UN Model Regulations may serve as a reference for the structure of these documents. Their general structure is presented in Table 8-1.

In this chapter, the IAEA Specific Safety Requirements SSR-6 (Regulations for the Safe Transport of Radioactive Material (2025 Edition) [160]) (referred to as the Transport Regulations) are described with a focus on the practical aspects of the transport of NORM. The main areas considered are (with exceptions specifically mentioned);

- large amounts of materials (1 Mg or more),
- radionuclides of natural origin with half-lives longer 100 days.

Radionuclides of natural origin, such as U-235, that are used for their nuclear or radiation properties are not considered.

TABLE 8-1: GENERAL STRUCTURE OF UN MODEL REGULATIONS

Part	Title	Content relevant for NORM practitioners
Part 1	General Provisions, Definitions, Training and Security	Contains the scope and application of the regulations. Definition of radioactive material. Description of conditions where regulations "Do Not Apply" (cf. Chapter 8.2.3).
Part 2	Classification	Defines classes of hazardous goods (→ Class 7: radioactive materials) and gives the specifications for classifying radioactive materials that have to be transported with application of the regulations (LSA, SCO, exempted packages)
Part 3	Dangerous good list, special provisions and exceptions	No relevant provisions for radioactive materials
Part 4	Packing and tank provisions	The packing provisions for radioactive materials summarise (and repeat) the provisions on packing in Part 2
Part 5	Consignment procedures	Contains provisions on marking, labelling, and documentation
Part 6	Requirements for the construction and testing of packaging and containers	Not relevant for practices with NORM
Part 7	Provisions concerning transport operations	Not relevant for practices with NORM

It is important to note that the Transport Regulations were developed to provide an acceptable level of control of the radiation (and other nuclear risks) to people, property and the environment that are associated with the transport of radioactive material, and storage incident to transport. Their limit values and requirements are mainly based on conservative models that consider exposure due to accidents rather than exposure of the public during transportation itself.

Radiological protection in the Transport of Regulations is mainly through the containment of radioactive materials and the control of external radiation levels. The Regulations cover all radioactive materials and apply to all modes of transport: land, water, and air.

Responsibilities of each party involved are as follows:

The consignor is responsible for the packaging, labelling, and accurate documentation.

The carrier is responsible for carriage (including proper towage), interim storage, undelivered packages, radiation protection, training of drivers and storekeepers.

The driver is responsible for the safety and security of the load and emergency procedures.

> **Note:** Sections 8.2 and 8.3 summarize the Transport Regulations, with a clear focus on the transport of NORM. For this purpose, text passages taken from the IAEA publication [160] are interpreted. Passages that refer to artificial radionuclides or fissile materials are omitted. Similarly, parts of the Transport Regulations which may only be relevant for NORM in very exotic conditions (e.g., LSA-III) are not considered. To keep the content manageable, details that are less important in normal cases are also omitted. Therefore,

if unanswered questions remain in individual cases, the Transport Regulations or the corresponding national laws or regulations must be used.

8.2 How to classify NORM for transport?

8.2.1 Background

Because NORM in industrial processes occurs in bulk amounts, the application of the Transport Regulations depends mainly on the activity concentration (this is because the total activity values are usually exceed). Based on this, there are different levels with graded requirements (see Figure 8-2):

- Materials are exempt from the Transport Regulations and can be considered "non-radioactive".
- Material which may be defined as radioactive, but the Transport Regulations do not apply.
- Materials for which the Transport Regulations have to be applied with a graded system.

NORM can fall into any level of application, depending on the radionuclides, volume and their concentrations.

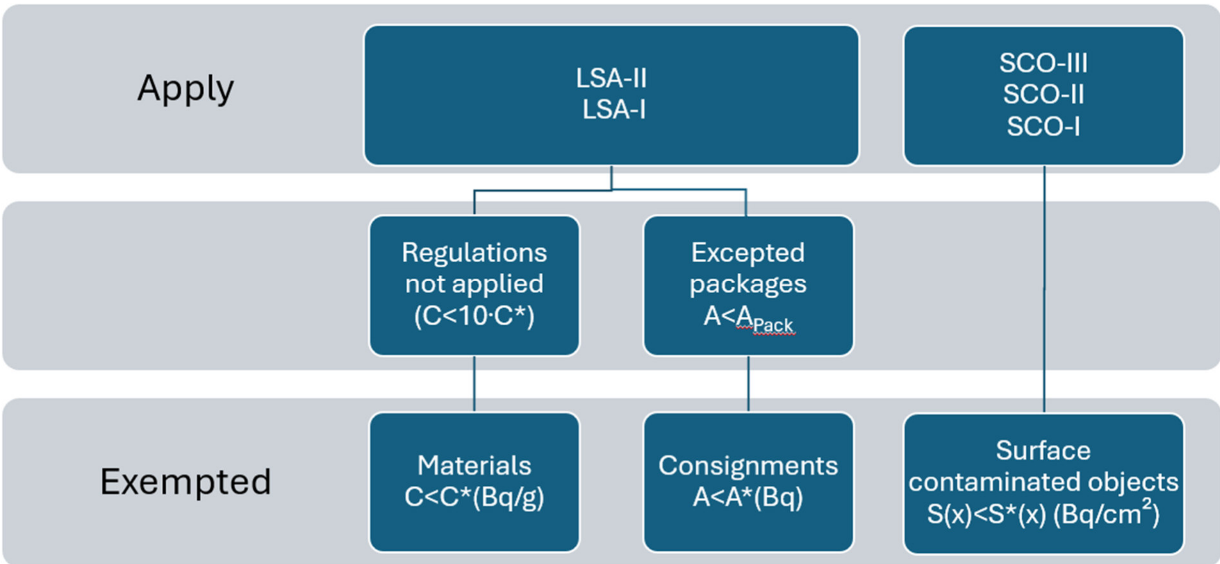


FIGURE 8-2: SCHEMATIC OVERVIEW OF THE REGULATORY LEVELS IN THE TRANSPORT REGULATIONS. SYMBOLS WITH AN ASTERIX DENOTE THE LIMIT VALUES FOR THE ACTIVITY CONCENTRATION (C*), THE TOTAL ACTIVITY (A*), AND THE SURFACE CONTAMINATION (S*)

A special challenge for NORM is the application of the Transport Regulations for surface contaminated objects (Chapter 8.2.5).

Transport Regulations should not be applied to sufficiently low activity concentrations. Small amounts of materials can be transported with reduced requirements in "excepted consignments".

An indispersible solid *radioactive material* or a sealed capsule containing *radioactive material can be transported as "special form radioactive material". However, this term is usually not applicable to* NORM.

8.2.2 What Materials are Exempted as "Non-radioactive"?

The Transport Regulations para. 236. define:

> Radioactive material shall mean any material containing radionuclides where both the activity concentration **and** the total activity in the consignment exceed the values specified in paras 402–407.

The values of total activity in the paras 402 - 407 for radionuclides occurring in NORM are in the order of 0.1 kBq – 10 kBq (see Table 8-6). Therefore, these values are usually exceeded if the mass of a (non-exempted) NORM is higher than about 10 kg. This means that only small parcels (e.g. samples) with activity concentrations higher than the activity concentration limit can be consigned as non-radioactive.

The main factor for classifying NORM is activity concentration because in industry, masses larger than several tonnes (Mg) are handled or processed. This is true for the transportation of exempted packages up to several tonnes (Mg) of NORM (see Chapter 8.2.6).

The activity concentration values relevant for NORM are given in Table 8-2. Radionuclides with half-lives below 100 days (e.g. Th-234, Ra-224) are not included in Table 8-2 because they can be assumed to be in equilibrium with their longer-lived parents. Two (less important) exceptions are Th-227 and Ra-223, which are not included in the progeny of Ac-227+.

For checking the compliance with the exemption value in a mixture of radionuclides, the sum of activity concentrations

$$\boldsymbol{C_m = \sum_i C_i}$$ ***EQU. 8-1***

must be compared with a Basic Radionuclide Value (BRV(C)) for the activity concentration limit. The activity concentration complies with the exemption limit if

$$C_m < BRV(C)$$

The BRV must be calculated as follows:

$$\boldsymbol{BRV(C) = \frac{1}{\sum_i \frac{f_i}{C_i^*}}}$$ ***EQU. 8-2***

where:

$f_i = C_i/C_m$ is the fraction of activity concentration of radionuclide i in the mixture

C_i^* is the activity concentration limit for radionuclide *i*

Equations 8-1 and 8-2 are called the summation rule. They can be applied to total activities A, too. In such a case, BRV(A) is calculated according to Equation 8-2. (Note that the values in the table only apply when the "included progeny" are in equilibrium with the parent radionuclide.)

TABLE 8-2: ACTIVITY CONCENTRATION LIMITS FOR EXEMPT MATERIAL FOR NORM-SPECIFIC RADIONUCLIDES

Parent nuclide	**Included progeny**	**Activity concentration limit C*** [Bq/g]
Th(nat)	Ra-228, Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Tl-208 (0.36), Po-212 (0.64)	1
Th-232		10
Ra 228+	Ac-228	10
Th 228+	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Tl-208 (0.36), Po-212 (0.64)	1
U(nat)	Th-234, Pa-234m, U-234, Th-230, Ra-226, Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210	1
U-238+	Th-234, Pa-234m	10
U-234		10
Th-230		1
Ra 226+	Rn-222, Po-218, Pb-214, At-218, Bi-214, Rn-218, Po-214, Tl-210	10
Pb-210+	Bi-210, Po-210	10
Po 210		10
U-235+	Th-231	10
Pa-231		1
Ac-227+	Fr-223, At-219, Bi-215, Po-215, Pb-211, Bi-211, Tl-207, Po-211	0.1
Th-227		10
Ra-223+	Rn-219, Po-215, Pb-211, Bi-211, Tl-207	100
K-40		100#

never exceeded in natural potassium

8.2.3 When Transport Regulations Do Not Apply?

According to [160] para. 107(f) the Regulations do not apply to:

> *"Naturally occurring radioactive material, provided the activity concentration of the material does not exceed 10 times the values specified in the Appendix, or as calculated in accordance with paras 405 and 406. For naturally occurring radioactive material where the radionuclides are not in secular equilibrium, the calculation of the activity concentration shall be performed in accordance with para. 405.*

This clause is important for many practices because bulk volumes of NORM that meet this criterion can be transported without having to apply the requirements of the Transport Regulations.

> **Note:** The formulation "Regulations do not apply" does not mean that the materials are considered to be non-radioactive in legal terms. This is important in any case of an accident where released materials that exceed the exemption limits must be considered as radioactive substances.

It is important to note that Clause 107(f) refers to the summation rule (mentioned earlier and para 405 of the Transport Regulations) for materials that are not in secular equilibrium. For materials that are in secular equilibrium, the values of U(nat) and Th(nat) are used. As noted earlier in this handbook, it is possible to estimate whether a material is in equilibrium based on its processing.

> **Note:** There is a case where a material contains both U(nat) and Th(nat) (for example a rare earth mineral), then requirements are applied to the sum U(nat) + Th(nat).

However, if the materials have been processed by chemical treatments or high temperatures, the radioactive equilibria are usually disturbed. In such cases, the summation rule must be applied. Examples of how to assess such materials and the consequences of applying the summation rule are given in the chapter on case studies (Chapter 8.4)

> **TIP:** Please be aware that the former formulation, which excluded materials that have been processed for the extraction of their radionuclides and the intended use of these radionuclides, was already modified in the 2018 Transport Regulations (as well as in the UN Model Regulations 2023).

8.2.4 What Does Low Specific Activity (LSA) Material Mean?

NORM that is subject to the transport regulations can usually be classified depending on the activity concentration as **LSA-I.** In very few cases, it may be classified **LSA-II.** The activity concentration limits of LSA-II are so high that they are practically not reached by NORM. For instance, the specific activity of Th-232 metal is about 4,000 Bq/g, and the limit for LSA-II is 100,000 Bq/g. Therefore, LSA-III does not play a role in the transport of NORM. References to LSA III are included in this Handbook solely for completeness.

The LSA criteria, according to the Transport Regulations, are:

LSA-I:

a) Uranium and thorium ores and concentrates of such ores, and other ores containing NORM.
b) (Chemically pure) natural uranium, natural thorium or their compounds or mixtures, that are unirradiated and in solid or liquid form.
c) Radioactive material for which the A_2 value is unlimited. These are NORM with U(nat), U-238, U-235, and Th(nat).
d) Other radioactive material in which the activity is distributed throughout and the estimated average activity concentration does not exceed 30 times the values for the activity concentration specified in paragraphs 402–407 of the SSR-6 (see Table 8-3).

LSA-II:

a) Tritiated water with an activity concentration of up to 0.8 TBq/L (not relevant for NORM).
e) Other material in which the activity is distributed throughout, and the estimated average activity concentration**Error! Bookmark not defined.** does not exceed 10^{-4} A_2/g for solids, and 10^{-5} A_2/g for liquids (see Table 8-3).

LSA-III: Solids (e.g., consolidated wastes), excluding powders, in which:

a) The radioactive material is distributed throughout a solid or a collection of solid objects, or is essentially uniformly distributed in a solid compact binding agent (e.g. concrete, bitumen, ceramic);
b) The estimated average activity concentration of the solid, excluding any shielding material, does not exceed 2×10^{-3} A_2/g (see Table 8-3).

In Table 8-3 the A2-values according to IAEA SSR-6 (2018) [160] and (2025) [163] are listed side by side and show that there are significant differences for some radionuclides. The most relevant differences occur for Ra-228 and Pb-210.

TABLE 8-3: A2-VALUES ACCORDING TO IAEA SSR-6 (2018) AND (2025), AND ACTIVITY CONCENTRATION LIMITS FOR LSA BASED ON A2-VALUES ACCORDING TO IAEA SSR-6 (2025)

Parent nuclide Included decay products see Table 8-2	**A2 (2018)** [GBq]	**A2 (2025)** [GBq]	**LSA-I** [Bq/g]	**LSA-II (solid)** [Bq/g]	**LSA-II (Liquid)** [Bq/g]	**LSA-III** [Bq/g]
Th(nat)	Unlimited	Unlimited	30	Unlimited	Unlimited	Unlimited
Th-232	Unlimited	Unlimited	300	Unlimited	Unlimited	Unlimited
Ra 228	20	1	300	100 000	10 000	1 000 000
Th 228	1	0.9	30	90 000	9 000	900 000
U(nat)	Unlimited	Unlimited	30	Unlimited	Unlimited	Unlimited
U-238	Unlimited	Unlimited	300	Unlimited	Unlimited	Unlimited
U-234	90(f) – 20(m) - 6 (s) #	200(f) - 20 (m) 6 (ms) – 2 (s)#	300	Depends on chemical form*		
Th-230	1	1	30	100 000	10 000	1 000 000
Ra 226	3	2	300	200 000	20 000	2 000 000
Pb-210	50	3	300	300 000	300 000	3 000 000
Po 210	20	20	300	2 000 000	200 000	2 000 000
U-235	Unlimited	Unlimited	300	Unlimited	Unlimited	Unlimited
Pa-231	0.4	0.5	30	50 000	5 000	500 000
Ac-227	0.09	0.5	3	50 000	5 000	500 000

f – m – s are abbreviations for fast, medium, and slow lung absorption rates. Note: letters in brackets in SSR-6 (2025) refer to footnotes in the document, not to lung absorption rates!
´* According to footnote (g) in SSR-6 (2025), the lung absorption rate "moderate to slow" (ms) should be applied for uranium in natural minerals (NORM)

The LSA classification refers to the specific requirements for transport, such as packaging and labeling. **LSA-I** material may be transported unpacked, subject to certain conditions. **NORM LSA** may also be transported in industrial packages such as drums, bags, and ISO containers and in IP1 packages due to low activity per unit mass. It may be transported in IP3 packages, very rarely, because it would take a vast mass of material to reach such levels.

8.2.5 What is a Surface Contaminated Object (SCO)?

SCO is a solid object which is not itself radioactive, but which has radioactive material distributed on its surfaces. A SCO that is subject to the Transport regulations could be classified as SCO-I, SCO-II or SCO-III, depending on the surface activity concentration, the radionuclides involved and whether the contamination is fixed or non-fixed.

SCO-I: A solid object on which:

i) The non-fixed contamination on the accessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed **4 Bq/cm²** for beta and gamma emitters and low toxicity alpha emitters, or **0.4 Bq/cm²** for all other alpha emitters;
ii) The fixed contamination on the accessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed **4 × 10^4 Bq/cm²** for beta and gamma emitters and low toxicity alpha emitters, or **4 000 Bq/cm²** for all other alpha emitters;
iii) The non-fixed contamination plus the fixed contamination on the inaccessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed **4 × 10^4 Bq/cm²** for beta and gamma emitters and low toxicity alpha emitters or **4 000 Bq/cm²** for all other alpha emitters.

SCO-II: A solid object on which either the fixed or non-fixed contamination on the surface exceeds the applicable limits specified for SCO-I above and on which:

i) The non-fixed contamination on the accessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed **400 Bq/cm²** for beta and gamma emitters and low toxicity alpha emitters, **or 40 Bq/cm²** for all other alpha emitters;
ii) The fixed contamination on the accessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed **8 × 10^5 Bq/cm²** for beta and gamma emitters and low toxicity alpha emitters, or **8 × 10^4 Bq/cm²** for all other alpha emitters;
iii) The non-fixed contamination plus the fixed contamination on the inaccessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed **8 × 10^5 Bq/cm²** for beta and gamma emitters and low toxicity alpha emitters, or **8 × 10^4 Bq/cm²** for all other alpha emitters.

SCO-III: A large solid object that, because of its size, cannot be transported in a type of package described in these Regulations, and for which:

i) All openings are sealed to prevent the release of radioactive material during the conditions specified in para. 520(e);
ii) The inside of the object is as dry as practicable;
iii) The non-fixed contamination on the external surfaces does not exceed the limits for SCO-I letter i);
iv) The non-fixed contamination plus the fixed contamination on the inaccessible surface averaged over 300 cm^2 does not exceed **8 × 10^5 Bq/cm²** for beta and gamma emitters and low toxicity alpha emitters, or **8 × 10^4 Bq/cm²** for all other alpha emitters.

Low toxicity alpha emitters include:

- U_{nat}, [U_{dep}], Th_{nat}, ^{235}U, ^{238}U, ^{232}Th, ^{228}Th and ^{230}Th, when contained in ores or physical and chemical concentrates,
- Alpha emitters with a half-life of less than 10 days.

From the decay series alpha emitters, only Ra-226, Po-210, Pa-231, Th-227, Ra-223 are not included in the low toxicity alpha emitters. The latter three are from the U-235 series and must be considered only if radionuclides of this series are essentially important (e.g. Ac-227 contaminated lanthanum, see Chapter 7).

> **Note 1:** The criteria given above refer to the measured quantity "surface contamination" in Bq/cm^2 which are obtained by hand-held contamination monitors or wipe tests (see Chapter 5). Some practical challenges related to the determination of the surface contamination in industries involving NORM are described in Chapter 5.

> **Note 2:** Because many industries involving NORM are "dirty", the contaminations occurring in these industries are more or less thick layers. These layers may be solid incrustations, and it is difficult to decide what part of the layer is fixed or non-fixed. This may become a challenge if NORM-contaminated objects must be transported to a site for cleaning.

An additional problem is that surface contamination could include many different radionuclides. This is because nearly all NORM is a mixture of different radionuclides that belong to the U-238- and Th-232-decay series alpha emitters (Type α), low toxicity alpha emitters (Type α-L), and beta emitters (Type β) occur simultaneously in SCO with NORM. One beta emitter that may significantly contribute to the beta signal is K-40. This should be kept in mind when interpreting measurement results.

To get an impression of the theoretical surface contamination, Table 8-5 provide examples of "surface contamination" (SC) that is calculated for different radionuclide compositions. The examples assume: 1 Bq/cm^2, a 1 mm thick layer with a density of 1 g/cm^3, and an activity concentration of 10 Bq/g.

The examples aim to show that it is important to understand the contamination material, because different radionuclides have different limits.

TABLE 8-4: EXAMPLES OF DIFFERENT SURFACE CONTAMINATION MATERIALS FOR U-238-SERIES RADIONUCLIDES

			Materials with different radionuclide compositions (see note below table)					
Nuclide	Type	Unit	U(nat)	U(chem)	Th-230	Ra-226	Pb-210	Po-210
U-238	α-L	Bq/cm^2	1	1				
Th-234	β	Bq/cm^2	1	1				
Pa-234m	β	Bq/cm^2	1	1				
U-234	α-L	Bq/cm^2	1	1				
Th-230	α-L	Bq/cm^2	1		1			
Ra-226	α	Bq/cm^2	1			1		
Rn-222	α-L	Bq/cm^2	1			1		
Po-218	α-L	Bq/cm^2	1			1		
Pb-214	β	Bq/cm^2	1			1		
Bi-214	β	Bq/cm^2	1			1		
Po-214	α-L	Bq/cm^2	1			1		
Pb-210	β	Bq/cm^2	1			1	1	
Bi-210	β	Bq/cm^2	1			1	1	

Po-210	α	Bq/cm²	1			1	1	1
SC	β	Bq/cm²	6	2	0	4	2	0
SC	α-L	Bq/cm²	6	2	1	3	0	0
SC	α	Bq/cm²	2	0	0	2	1	1

Note:

- Th-230 may represent contamination from acid leaching
- Ra-226 may represent scales
- Pb-210 and Po-210 may represent contamination from different smelting dust or fumes

TABLE 8-5: EXAMPLES OF DIFFERENT CALCULATED SURFACE CONTAMINATION MATERIALS FOR DIFFERENT RADIONUCLIDE COMPOSITIONS WITH TH-232 -SERIES RADIONUCLIDES

			Materials with different radionuclide compositions (see note below table)		
Nuclide	Type	Unit	Th(nat)	Th(chem)	Ra-228
Th-232	α-L	Bq/cm²	1	1	
Ra-228	β	Bq/cm²	1	0.5	1
Ac-228	β	Bq/cm²	1	0.5	1
Th-228	α-L	Bq/cm²	1	0.5	1
Ra-224	α-L	Bq/cm²	1	0.5	1
Rn-220	α-L	Bq/cm²	1	0.5	1
Po-216	α-L	Bq/cm²	1	0.5	1
Pb-212	β	Bq/cm²	1	0.5	1
Bi-212	α-L	Bq/cm²	0.36	0.18	0.36
Bi-212	β	Bq/cm²	0.64	0.32	0.64
Po-212	α-L	Bq/cm²	0.64	0.32	0.64
Tl-208	β	Bq/cm²	0.36	0.18	0.36
SC	β	Bq/cm²	4	2	4
SC	α-L	Bq/cm²	4	2	4
SC	α	Bq/cm²	4	2	4

Note:

- Ra-228 may represent contamination from scales

From the calculated SC values in Table 8-5 the following conclusions can be derived:

- Compared to the limits given in the criteria SCO-I letter i) the limiting value is frequently that of alpha emitters not classified as low toxicity (0.4 Bq/cm²). This value cannot be directly measured. Its determination requires knowledge of the nuclide composition, i.e. a characterization of the NORM.
- The limit for a fixed contamination of 8 x 10^4 Bq/cm² according to SCO-I Letter II) would require a contamination with uranium or thorium minerals of 5 g/cm² pure thorium (specific activity 4 kBq/g) or 3 g/cm² pure uranium (12.3 kBq/g). These figures

demonstrate that NORM will normally comply with the criterium SCO-I letter ii). Otherwise, the layer has to be several cm (or even dm) thick and can be considered as volume and not as a surface contamination.

While the beta–gamma signal detected in a monitor can be considered representative for the 1 mm thick layer, the main part of the emitted alpha particles will be absorbed. An alpha signal measured over such a contamination layer stems from a very thin layer at the surface (a few micrometers) and is not representative of the surface contamination.

Classification of NORM-contaminated objects as SCO according to the Transport Regulation is frequently arbitrary, depending on the individual interpretation of the measurements.

TIP: Understanding the type of contamination is important to enable proper decision making on surface contamination.

8.2.6 What are Exempted Consignments and Excepted Packages?

Small amounts of NORM with a total activity below the limits given in Table 8-6 can be sent as an exempted consignment independently of their activity concentration. The contents of such a consignment are non-radioactive under the hazardous goods regulations.

The other possibility for NORM transport with reduced requirements is as an excepted package. A package may be classified as an excepted package if it meets one of the following conditions:

- It is an empty package having contained radioactive material.
- It contains instruments or articles not exceeding the activity limits specified in Transport Regulations (Table 8-6).
- It contains articles manufactured of natural uranium, or natural thorium (e.g., thoriated welding rods).
- It contains solid or liquid radioactive material not exceeding the activity limits specified in Table 8-6.

Note: Whether sludge is categorized as solid or liquid is a matter of judgment in each individual case.

An excepted package does not mean the contents are non-radioactive. As mentioned in Section 8.2.2 materials are exempted from the regulations only if the total activity complies with the values for an exempt consignment (see Table 8-6). An excepted package contains radioactive material, but no outside labels are required. However, transport documents are obligatory for each excepted package. Moreover, according to para 516 [4], the dose rate at the external surface must be below 5 µSv/h.

Hint: Have information on the material inside the package to inform workers who might open the package.

NORM may be transported as an **excepted package under category I-White** if the dose rate at the surface is less than 5 µSv/h (see Table 8-9).

As the activity limits for U(nat) and Th(nat) are unlimited, ores and minerals for which an activity equilibrium can be assumed can be transported unpackaged or in any quantity as an excepted package without any limits of activity concentration. However, the dose rate must comply with the 5 µSv/h limit.

The case is different for NORM with disturbed activity equilibria. Some examples of activity concentrations that demonstrate roughly the ranges allowed for excepted packages are given in Table 8-7. The values were calculated for example material with different radionuclide compositions and a package mass of 200 kg (0.2 Mg), referring to the equations given in Section 8.2.2.

TABLE 8-6: ACTIVITY LIMITS FOR AN EXEMPT CONSIGNMENT AND EXCEPTED PACKAGES FOR RADIONUCLIDES RELEVANT FOR NORM. DATA REFER TO IAEA SSR-6 (2025)

Parent nuclide included decay products see Table 8-2	**A2 (2025)**	**Excepted Package (Solid content)**	**Excepted Package (Liquid content)**	**Exempted Consignment**
	[GBq]	[Bq]	[Bq]	[Bq]
Th(natural)	Unlimited	Unlimited	Unlimited	1 000
Th-232	Unlimited	Unlimited	Unlimited	10 000
Ra 228+	1	1 000 000	100 000	100 000
Th 228+	0.9	900 000	90 000	1 000
U(nat)	Unlimited	Unlimited	Unlimited	1 000
U-238+	Unlimited	Unlimited	Unlimited	10 000
U-234	6 *	6 000 000*	600 000*	10 000
Th-230	1	1 000 000	100 000	10 000
Ra 226+	2	2 000 000	200 000	10 000
Pb-210+	3	3 000 000	300 000	10 000
Po 210	20	20 000 000	2 000 000	10 000
U-235+	Unlimited	Unlimited	Unlimited	10 000
Pa-231	0.5	500 000	50 000	1 000
Ac-227+	0.5	500 000	50 000	1 000
K-40	Unlimited	Unlimited	Unlimited	1 000 000#

´* values hold for materials classified between moderate and slow lung absorption (g). Higher values for fast lung absorption, lower values for slow lung absorption. # not relevant for natural potassium because the highest activity concentration of natural K-40 of 31 Bq/g is far below the concentration limit for exempt material of 100 Bq/g

TABLE 8-7: ACTIVITY CONCENTRATION LIMITS OF EXCEPTED PACKAGES (MASS 200 KG). A* REFERS TO IAEA SSR-6 (2025)

Example Materials		f_i	A* (MBq)	BRV(A) (MBq)	C(limit) (Bq/g)
Leaching residue	U-238+	0.15	U	2.1	1.6
	U-234	0.15	6		1.6
	Th-230	0.15	1		1.6
	Ra-226+	0.2	2		2.1
	Pb-210+	0.12	3		1.2
	Th-232	0.07	U		0.7
	Ra-228+	0.09	1		0.9
	Th-228+	0.07	0.9		0.7
Scale from oil production	Ra-226+	0.5	2	1.8	4.4
	Pb-210+	0.3	3		2.7
	Ra-228+	0.09	1		0.8
	Th-228+	0.11	0.9		1.0
Filter dust from thermal processes	Pb-210+	1.0	3	3	15

Iron slag	U-238+	0.22	u	2.7	2.9
	U-234	0.22	6		2.9
	Th-230	0.22	1		2.9
	Ra-226+	0.22	2		2.9
	Pb-210+	0.02	3		0.3
	Th-232(nat)	0.10	u		1.3

The results in Table 8-7 are higher by a factor of 3 - 4 compared to the values obtained if the exemption limits C* of Table 8-2 are applied. However, because the Regulation does not apply to concentrations 10 times higher than the exemption limits (see Chapter 8.2.3) the excepted package allows higher concentrations only if the packed mass is less than 100 kg.

8.2.7 What are the Requirements for Measurements?

Determining the classification of NORM for the Transport Regulations is based on an understanding of the radionuclides and activity. How this information is obtained and what quality it needs to be is not specified in the Transport Regulations.

For NORM, all radionuclides are from the three natural decay series and K-40 and are therefore known. If the materials are in "undisturbed state", then the radionuclides can be assumed to be in secular equilibrium. For material that has been treated, and individual activities of some of the radionuclides are not known, the Transport Regulations para. 406 provides grouping of various radionuclides. By using the lowest radionuclide value, as appropriate for the radionuclides in each group, the summation rule can be applied. Groups may be based on the total alpha activity and the total beta/gamma activity, when these are known, using the lowest radionuclide values for the alpha emitters or beta/gamma emitters, respectively.

In Chapter 5 (Characterization) of this Handbook, there is some information that will be helpful in understanding radionuclide composition of various materials.

8.3 What Provisions Must be Considered at Packaging?

8.3.1 What Types of Packaging are Possible?

"Package" shall mean the complete product of the packing operation, consisting of the packaging and its contents prepared for transport.

NORM, whose activity concentrations require the application of the Transport Regulations, can be carried unpacked as loose bulk material if it is classified as LSA-I or SCO-I or (in case of very large objects) SCO-III. Unpacked also means transport in undefined bags, unspecified drums, or other not specifically approved packages. Otherwise, the radioactive material must be packed in approved packages. Industrial packages must be suitable for containing radioactive material and preventing the spread of radioactivity in the event of an incident during transport.

The type of package depends on the:

- the activity of material,
- radionuclides present,
- form of NORM (liquid, or solid).

Packaging for NORM must ensure that the contents are retained under "routine conditions of transport". This does not have to be a rigid box, e.g., a pallet of drill core trays securely wrapped in plastic.

The overall aim is to ensure that the package safely secures the radioactive material.

For international transport of packages, the package may require approval from a competent authority for package design or shipment. This may vary from country to country.

Overall, all packages must include the UN number, proper shipping name, categorization, labelling, and marking shall be in accordance with the certificate of the country of origin of the design.

For solid NORM classified as LSA-I or SCO-I, which are packaged for transported, an industrial package Type 1 (Type IP-1) is sufficient. This is independent of whether the package is exclusively used for NORM or not.

For solid NORM classified LSA-II or SCO-II, or liquids classified LSA-I, an industrial package of Type 2 (Type IP-2) must be used. Other types of packages (IP-3, Type A, B, or C) mentioned in the Transport Regulations do not play a role in transporting NORM.

8.3.2 How to Mark and Label Packages, Containers, or other Consignments?

For each package or overpack, the UN number and proper shipping name shall be determined.

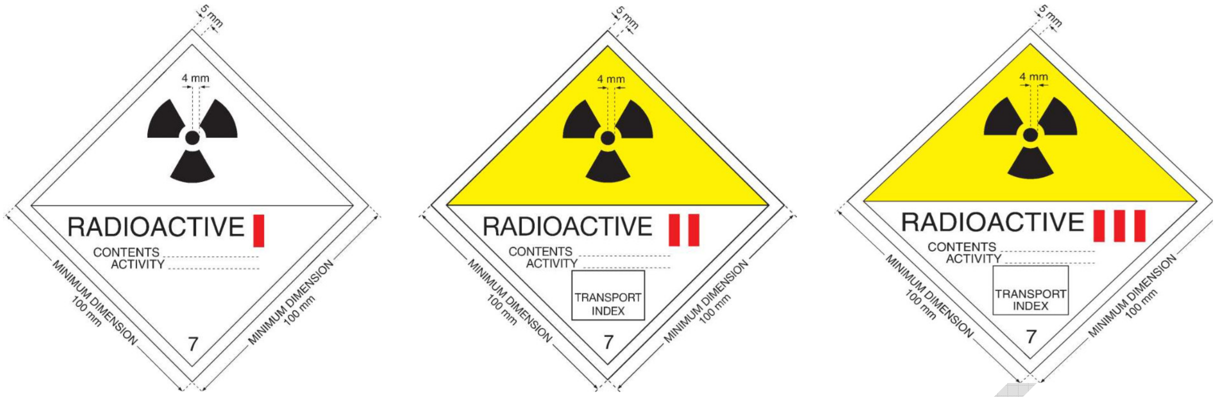
The UN numbers relevant to NORM are shown in Table 8-8.

TABLE 8-8: UN NUMBERS RELEVANT TO NORM, PROPER SHIPPING NAMES AND DESCRIPTIONS

UN number	Proper shipping name and description
2910	RADIOACTIVE MATERIAL, EXCEPTED PACKAGE — LIMITED QUANTITY OF MATERIAL
2912	RADIOACTIVE MATERIAL, LOW SPECIFIC ACTIVITY (LSA-I), non-fissile or fissile-excepted
3321	RADIOACTIVE MATERIAL, LOW SPECIFIC ACTIVITY (LSA-II), non-fissile or fissile-excepted
3322	RADIOACTIVE MATERIAL, LOW SPECIFIC ACTIVITY (LSA-III), non-fissile or fissile-excepted
2913	RADIOACTIVE MATERIAL, SURFACE CONTAMINATED OBJECTS (SCO-I, SCO-II or SCO-III), non-fissile or fissile-excepted

Labels should be affixed to two opposite sides of the package or overpack, or to all four outsides of a freight container or tank.

The category is determined depending on the dose rate at any point on the external surface, the categories of the packages, overpacks, and freight containers (Table 8-9). The category labels are shown in Figure 8-3.



Category I-WHITE label   Category II-YELLOW label   Category III-YELLOW label

FIGURE 8-3: CATEGORY LABELS

Additionally, the **Transport Index (TI)** has to be determined for the package, an overpack, a freight container, or even an unpacked load classified as LSA-I, SCO-I, or SCO-III.

The TI of a package represents the radiation level 1 m from the package exterior. According to IAEA SSR-6 [163] it is calculated from a measured dose rate

$$TI = DR(1m)(mSv/h) \cdot 100$$

and rounded to the next higher decimal digit. E.g., if the dose rate at 1 m is DR(1m) = 12.4 µSv/h = 0.0124 mSv/h, the TI is 1.3. If the dose rate DR(1m) is less than 0.5 µSv/h (0.0005 mSv/h), any calculated TI < 0.05 is rounded to zero.

In the Transport Regulations, para 523-524 [163] dose rates are given that can be applied to uranium and thorium ores and their concentrates. The maximum dose rate at any point 1 m from the external surface of the load may be taken as:

(i) 0.4 mSv/h (TI = 40) for ores and physical concentrates of uranium and thorium;

(ii) 0.3 mSv/h (TI = 30) for chemical concentrates of thorium;

(iii) 0.02 mSv/h (TI = 2) for chemical concentrates of uranium, other than uranium hexafluoride.

TABLE 8-9: CATEGORIES OF PACKAGES, OVERPACKS, AND FREIGHT CONTAINERS

Transport Index	Maximum dose rate at any point on external surface	Category
0[a]	<0.005 mSv/h	I-WHITE
0 – 1	0.005 – 0.5 mSv/h	II-YELLOW
1 – 10	0.5 – 2 mSv/h	III-YELLOW
>10	2 – 10 mSv/h	III-YELLOW[b]

[a] If the measured TI is not greater than 0.05, the value quoted may be zero
[b] Shall also be transported under exclusive use except for freight containers

For a freight container used as packaging or a freight container loaded with several packages, the TI must be enhanced by a multiplication factor depending on the sizes of the load (Table 8-10). The same holds for a tank, or unpackaged LSA-I, SCO-I, and SCO-III.

TABLE 8-10: MULTIPLICATION FACTORS FOR TANKS, FREIGHT CONTAINERS AND UNPACKAGED LSA-I, SCO-I AND SCO-III

Size of load	Multiplication factor
≤ 1 m²	1
1 m² < size of load ≤ 5 m²	2
5 m² < size of load ≤ 20 m²	3
20 m² < size of load	10

Note: The relationship between the maximum dose rate at any point on the external surface (which determines the Category) and the Transport Index depends on the package size. Drums with volumes of 50 L to 200 L will have dose rate ratios DR(1m)/DR(Surface) of about 1 % - 2 %. Therefore, if the surface dose rate is less than 20 µSv/h, the measured dose rate at 1 m will be significantly influenced by background. This effect will be relevant if background dose rates enhance the measured value above 0.5 µSv/h.

8.3.3 What Else is Necessary for Complete Documentation?

Dangerous goods declarations need to be prepared with the following text:

> *"I hereby declare that the contents of this consignment are fully and accurately described above by the proper shipping name and are classified, packaged, marked and labelled/placarded, and are in all respects in proper condition for transport according to applicable international and national governmental regulations."*

The consignor must the identification of the consignor and consignee, including their names and addresses, and the following information in the transport documents and with each consignment:

- The UN class number "7" and the UN number (see Table 8-8)
- The proper shipping name, e.g. LSA-I
- The subsidiary hazard class or division number(s) if required
- The name or symbol of each radionuclide or, for mixtures of radionuclides, an appropriate general description or a list of the most restrictive nuclides.
- A description of the physical and chemical form of the material, or a notation that the material is special form radioactive material or low dispersible radioactive material. A generic chemical description is acceptable for chemical form.
- The maximum activity of the radioactive contents during transport expressed in units of Becquerels (Bq) with the appropriate SI prefix symbol.
- The category of the package, overpack or freight container, as I-WHITE, II-YELLOW, III-YELLOW.
- The TI as determined (except for category I-WHITE).

For large packages, **placards** should be used. Placards go on the vehicle on 2 sides and on the rear, and on all 4 sides of the container.

FIGURE 8-4: PLACARD

8.3.4 Example of the Transport Document

Figure 8-5 shows an example of a transport document for the carriage of a 200-liter drum with dry radium scales. Activity concentrations of this drum have been measured, with results compiled in Table 8-11. The dose rate at a distance of 1 m was measured to be 4.2 µSv/h.

TABLE 8-11: ACTIVITY CONCENTRATIONS OF DRY SCALE RESIDUES

	Ra-228	Th-228	Ra-226	Pb-210
C in Bq/g	45	55	95	66

Consignment Cert for CLASS 7 Radioactive Material The Carriage of Dangerous Goods etc Regulations SI2009 No. 1348	
From Consignor **Name & Address + contact & tel. no.**	**To Consignee** **Name & Address: contact & tel. no.**
Description of Consignment: UN No. 3321 (LSA-II) **& Shipping Name; subsidiary risks: metallic mercury**	
Maximum dose-rate at the surface of the container: 140 µSv/h	
Radionuclide: Ra-226, Ra-228 (Th-228)	
Physical & Chemical form: solids	
Activity in MBq: 75	
Package Type: Type A / IP-I ???	
Category: II-YELLOW	
Transport Index: 0.5	
Contamination Checks: < 4 Bq/cm² (β, γ, U & Th); < 0.4 Bq/cm² (other alphas)	
Shippers Declaration	**Sign, Print Name, Date**

FIGURE 8-5: ***EXAMPLE of a TRANSPORT DOCUMENT for the carriage of drums with dry radium scales***

8.4 Example Transport Questions

This section provides some questions for the reader. Answers are provided in Section 8.6.

8.4.1 Case 1 – Bulk Amounts Phosphogypsum

A phosphogypsum heap of 5000 m³ is to be remediated. To do this, it must be removed and taken to a landfill site. A truck will carry a total mass of 20 Mg (tonnes). The activity concentration of the phosphogypsum is known from three samples (Table 8-12).

TABLE 8-12: ***ACTIVITY CONCENTRATIONS OF PHOSPHOGYPSUM SAMPLES***

Sample	Unit	Ra-228	Th-228	U-238	Ra-226	Pb-210
1	Bq/g	0.05	0.05	0.20	0.40	0.45
2	Bq/g	0.03	0.02	0.3	1.6	1.3
3	Bq/g	0.02	0.02	0.22	0.9	1.1

Your task is to decide:

Q1-1: Is phosphogypsum a radioactive material according to the ADR-rules?
Q1-2: Does the transport require the application of ADR-Regulations?

8.4.2 Case 2 – Bulk Amounts Sludges

50 drums of sludge from an oil production company with a total mass of 18 Mg (tonnes) must be transported to an incineration facility for disposal. The activity concentrations of 12 drums were determined according to Table 8-13. The dose rates measured in contact with the drums are between 2 µSv/h and 10 µSv/h.

TABLE 8-13: ***CHARACTERISTICS OF DRUMS WITH OIL SLUDGE***

Drum	**Mass**	**Dry Matter**	**Pb-210**	**Ra-226**	**Ra-228**	**Th-228**
	kg	**%**	**Bq/g Dry Mass**			
3	270	22	61.8	42.7	14.1	18.2
5	310	18	28.9	49.4	26.1	29.4
13	360	27	32.6	26.7	13.0	12.2
18	350	25	63.2	79.2	26.0	28.0
22	390	31	11.0	26.1	22.9	21.0
26	270	11	103.6	171.8	40.0	50.9
31	300	18	15.0	21.7	13.3	16.1
33	440	41	54.6	75.9	50.0	55.6
39	380	30	81.3	94.7	74.3	83.3

40	370	29	5.2	6.6	2.8	3.1
44	340	24	3.8	5.8	1.3	1.3
49	370	29	3.8	6.2	2.4	3.1

Your task is to decide:

Q2-1: Does this transport require the application of hazardous goods regulations?
Q2-2: What labelling is required?

8.4.3 Case 3 – Small Quantities

You sent a package of 12 sludge samples (approx. 0.5 kg each) from an oil producer to a laboratory for radionuclide analysis. You did not know the activity concentrations, but you measured dose rates of 0.5 µSv/h to 12 µSv/h in direct contact with the samples. The dose rate measured in contact with the package was between 2 µSv/h and 4.5 µSv/h.

You sent the package as an exempted consignment. You justified your declaration by stating that the dose rate outside the package was below 5 µSv/h. After analyzing you obtained the results listed in #& from the laboratory.

Your task is to decide:

Q3-1: Was it correct to send the package as an exempted consignment?

8.4.4 Case 4 – Surface Contaminated Object (SCO) – 1

Consider a 2 Mg (tonne) front-end loader bucket that has been working with NORM. There is some rust on the bucket, and the alpha surface contamination levels are 1 Bq/cm² for a small area of the bucket (1 m x 0.2 m).

The user would like the bucket to be refurbished at a service center. He reads the provisions of ADR (2023) para. 2.7.2.1.2 (or UN Model Regulations para. 2.7.1.2):

> Contamination shall mean the presence of a radioactive substance on a surface in quantities in excess of 0.4 Bq/cm² for beta and gamma emitters and low toxicity alpha-emitters, or 0.04 Bq/cm² for all other alpha emitters.

Your task is to advise the user on how this bucket should be transported. What is your answer to the question:

Q4-1: Is the bucket considered to be a "radioactive item", and therefore, does it need to be serviced in a licensed facility?

8.4.5 Case 5 – Surface Contaminated Object (SCO) – 2

When you see this statement,

> Contamination shall mean the presence of a radioactive substance on a surface in quantities in excess of 0.4 Bq/cm² for beta and gamma emitters and low toxicity alpha-emitters or 0.04 Bq/cm² for all other alpha emitters

How do you apply it if you have to decide on the status of several components that are radioactively contaminated at the surface?

a) Both 0.4 Bq/cm² for beta and gamma emitters AND 0.4 Bq/cm² for low toxicity alpha emitters must be exceeded for classifying an item as contaminated?

or

b) 0.4 Bq/cm² must be exceeded for the TOTAL of the beta and gamma and low toxicity alpha emitters for classifying an item as contaminated?

Also, what do you do in practice:

i. If you are a staff member of a haulage company.
ii. If you are a consultant who advises a private mining company.
iii. If you are a staff member of the competent authority.

8.5 Conclusions

For the Transport of NORM, there are some key messages.

- The Transport Regulations (IAEA SSR6 [163]) outline the requirements for transport. It is a complex document, but it has all the answers.
- Take your time and do not be afraid to ask for help to interpret this document.
- For NORM, there is clause 107(f), which says that for some radioactive NORM material, the Transport Regulations do not apply.

8.6 Answers to Questions

Case 1 – Bulk amounts

Q1-1: Is phosphogypsum a radioactive material according to the ADR-rules?

Answer

According to the definition given in Section 8.2.2 and Section 8.2.6 the following criteria must be checked:

1) The sum of **total activities A** per consignment (here: truck load) exceeds the exempt-consignment activity limit → The content of the drum **may be radioactive material** if activity concentration exceeds its limit, too.
2) The sum of **activity concentrations C_m** in the load exceeds the BRV(C) → content of the drum **is radioactive material** if the total activity exceeds its limit, too.

With only 3 data points showing substantial variability for the main radionuclides (Pb-210, Ra-226) any estimate of the radioactivity in an individual truckload is uncertain. However, based on the general knowledge of the activity concentration in phosphogypsum (see Chapter 3), the values are in a reasonable range.

To determine whether the phosphogypsum in a truckload is radioactive, we can take a conservative approach and use the highest measured values for each radionuclide.

To make an accurate estimate, we must also consider that phosphogypsum contains radionuclides that were not measured. Because we consider a phosphogypsum pile that shall be remediated, we can assume that this pile is more than 30 years old and, consequently, the

Th-232-series is in equilibrium. The other long-lived radionuclides not included in the "+" notation of their precursors, U-234, Th-230, can be estimated by an indirect determination (see Chapter 5). In Please note that this set of radionuclides includes **all** radionuclides of the U-238 and Th-232 series due to the '+' notation.

Table 8-14 the modified data set is compiled. Please note that this set of radionuclides includes **all** radionuclides of the U-238 and Th-232 series due to the '+' notation.

TABLE 8-14: MODIFIED DATA SET OF PHOSPHOGYPSUM AND EVALUATION ACCORDING TO HAZARDOUS GOODS REGULATIONS

		Th(nat)	U-238+	U-234	Th-230	Ra-226+	Pb-210+	Sum
Max. C	Bq/g	0.05	0.3	0.3	1.6	1.6	1.3	5.15
Max. A	MBq	1	6	6	32	32	26	103
f_i	--	0.01	0.06	0.06	0.31	0.31	0.25	
C_i*	Bq/g	1	10	100	1	10	10	
A*	MBq	0.001	0.01	0.01	0.01	0.01	0.01	
f_i/C_i*	g/Bq	0.010	0.006	0.001	0.311	0.031	0.025	0.383
f_i/A*	1/MBq	9.7	5.8	5.8	31.1	31.1	25.2	109

The total activity of a truck load is 20 Mg (tonnes). This load contains a sum activity of A_m = 103 MBq.

The Basic Radionuclide Value (BRV(A)) for the total activity limit of an exempted consignment is $BRV(A) = \frac{1}{109\ 1/MBq} = 0.0092$ MBq. This value is much lower than the total activity of 103 MBq. Consequently, the truckload may contain radioactive material if the activity concentration exceeds the limit.

The sum of activity concentrations is C_m = 5.15 Bq/g (MBq/Mg).

The Basic Radionuclide Value (BRV(C)) for the activity concentration limit according to Equ. 8-2 results to $BRV(C) = \frac{1}{0.383\ g/Bq} =$ 2.6 Bq/g

Because both the sum of the total activities of 103 MBq is much larger than the BRV(A) limit of 0.0092 MBq, and the sum of the activity concentrations C_m = 5.15 Bq/g is larger than BRV(C) = 2.61 Bq/g, the **phosphogypsum is classified as a radioactive material**.

Additional comments:

a) Please note that the BRV(C) is strongly influenced by Th-230 because the activity concentration limit of this radionuclide is 1 Bq/g. i.e., it is 10 times lower than that of Ra-226! Neglection Th-230 will significantly underestimate the Basic Reference Value for the activity concentration.
b) In our estimates, we did not consider the U-235 series. However, we note that considering this series (after indirect determination of activity concentrations!) will

significantly lower BRV(C) to about 1.9 Bq/g due to the very low activity concentration limit of Ac-227 of 0.1 Bq/g.

Q1-2: *Does the transport require the application of ADR- Regulations?*

Answer

According to Section 8.2.3 the hazardous goods regulations do not apply to:

> *"Naturally occurring **radioactive material**, provided the **activity concentration** of the material does not exceed 10 times the values specified in the Appendix, … ".*

Therefore, only the activity concentration is decisive in determining whether hazardous goods regulation applies. In our case of phosphogypsum, the sum of activity concentrations is C_m = 5.15 Bq/g. This is much lower than the 10-fold BRV(C) of 26 Bq/g. Consequently, for the transport of phosphogypsum, **the hazardous goods regulations must not be applied.**

Additional comments:

a) Other regulatory labelling according to the national waste regulations, environmental laws, or occupational-safety marking rules (e.g., dust, pH, waste code) may be required.
b) Regarding radioactivity, we recommend stating (if useful!) **"NORM waste below ADR application level"**

Case 2 – Bulk amounts sludges

Q2-1: *Does this transport require the application of hazardous goods regulations?*

Answer

The criteria for transport hazardous good regulations are:

1) The sum of **total activities A** per consignment exceeds the exempt-consignment activity limit → The content of the drum **may be radioactive material** if activity concentration exceeds its limit, too.
2) The sum of **activity concentrations C_m in a drum** exceeds the BRV(C) → Content of the drum **is radioactive material** if the total activity in the drum exceeds its limit, too.
3) The sum of activity concentrations C_m in a drum exceeds 10 times the BRV(C) → **This drum must be transported according to the hazardous goods regulations.**

Regarding both the total activities and the activity concentrations, the four radionuclides Ra-228, Th-228, Ra-226, and Pb-210 are sufficient for the calculation of the sum values because sludge from oil production is a precipitation product where only these four radionuclides occur in significant amounts (cf. Chapter 3).

Furthermore, the relevant activity concentrations are those actually present in the drums, not the dry-matter activity concentrations determined in the laboratory. Therefore, the activity concentrations of the wet mass were calculated from the concentration values and the dry mass content given in Table 8-13. The results obtained are given in Table 8-15. In this table, the sum values C_m, A_m, the limit values C*, A*, and the corresponding Basic Radionuclide Values BRV are presented.

TABLE 8-15: EVALUATION AND CHECKING DATA OF OIL SLUDGE DRUMS FROM TABLE 8-13 REGARDING HAZARDOUS GOODS REGULATIONS (EXPLANATIONS SEE TEXT)

Drum	Mass	Pb-210+	Ra-226+	Ra-228+	Th-228+	C_m	BRV(C)	A_m	BRV(A)
	Kg	Bq/g Wet Mass				Bq/g	Bq/g	MBq	MBq
3	270	13.6	9.4	3.1	4	30.1	4.6	8.1	0.003
5	310	5.2	8.9	4.7	5.3	24.1	3.4	7.5	0.002
13	360	8.8	7.2	3.5	3.3	22.8	4.3	8.2	0.003
18	350	15.8	19.8	6.5	7	49.1	4.4	17.2	0.002
22	390	3.4	8.1	7.1	6.5	25.1	3.0	9.8	0.003
26	270	11.4	18.9	4.4	5.6	40.3	4.4	10.9	0.002
31	300	2.7	3.9	2.4	2.9	11.9	3.1	3.6	0.003
33	440	22.4	31.1	20.5	22.8	96.8	3.2	42.6	0.003
39	380	24.4	28.4	22.3	25	100.1	3.1	38.0	0.003
40	370	1.5	1.9	0.8	0.9	5.1	3.9	1.9	0.002
44	340	0.9	1.4	0.3	0.3	2.9	5.2	1.0	0.002
49	370	1.1	1.8	0.7	0.9	4.5	3.6	1.7	0.002
C*		10	10	10	1	31	7.8		
		Pb-210+	Ra-226+	Ra-228+	Th-228+				
A*	MBq	0.1	1.00E-03	1.00E-02	1.00E-02				

From the results presented in Table 8-15 the following conclusions follow:

1) The sum of total activities A exceeds **in all drums** the exempt-consignment activity limit → The content **of all drums may be radioactive material** if activity concentration exceeds its limit, too. Any consignment with the drums considered here will be classified as radioactive if the activity concentration exceeds the limits.
2) The sum of activity concentrations C_m **in all drums** exceeds the BRV(C) → Content **of all drums is radioactive material**.
3) The sum of activity concentrations C_m only in drums No. 18, 33, 39 exceeds 10 times the BRV(C) → **Only these three drums must be transported according to the hazardous goods regulations.**

Because only the sludge from 12 of 50 drums was analyzed in detail, any consignment should be classified as radioactive material that requires the application of hazardous goods regulations.

Note:

If any material exceeds a few hundred kg or even a tonne, the total activity A_m will never be lower than the activity level of an exempted consignment BRV(A). You can decide without the calculations demonstrated in Table 8-15. For small amounts, such as samples, a check is required.

If only one activity concentration of a radionuclide is 10 times higher than the concentration limit C* for exempt material (Table 8-2), then the sum of activity concentrations will exceed the

BRV(C), and you must not calculate the sums in detail. However, as you can see from the data for drum No. 18 in Table 8-15, it is possible that all concentrations are below 10 times the limit, but the summation still results in the limit being exceeded. We therefore recommend that, in all cases where at least one activity concentration exceeds 5 times the limit value, an evaluation using summation should be carried out.

Q2-2: *What labelling is required?*

This is oil sludge containing natural radionuclides (NORM). It is a solid mixture, likely not dispersible, so it qualifies as LSA-I (or LSA-II) material under ADR 2.7.2.3.1.2 and should be labelled with **UN 2912** number.

Measured dose rates are 2 – 10 µSv/h at contact with the drums, which bear a **Category II-YELLOW** label with **Class 7** trefoil.

The **Transport index (TI)** should be determined by measuring the dose rate at 1 m distance.

Case 3 – Small quantities

Q3-1: *Was it correct to declare the consignment 12 samples á 0.5 kg with oil sludge from* Table 8-13 *as a non-radioactive material?*

The answer is: **NO**. Although the surface dose rate was below 5 µSv/h, ADR 2.7 requires that both the dose and radionuclide-activity criteria be satisfied for exemption. C_m the parcel should have been classified and declared as Class 7 (radioactive material) — not simply as an exempt package.

TABLE 8-16: ***CHECKING THE COMPLIANCE OF SAMPLES TAKEN FROM THE OIL SLUDGE***

Sample from drum	Sample mass	C_m	A_m	BRV(A)
	kg	Bq/g wet mass	MBq	MBq
3	0.5	30.1	0.015	0.003
5	0.5	24.1	0.012	0.002
13	0.5	22.8	0.011	0.003
18	0.5	49.1	0.025	0.002
22	0.5	25.1	0.013	0.003
26	0.5	40.3	0.020	0.002
31	0.5	11.9	0.006	0.003
33	0.5	96.8	0.048	0.003
39	0.5	100.1	0.050	0.003
40	0.5	5.1	0.003	0.002
44	0.5	2.9	0.001	0.002
49	0.5	4.5	0.002	0.002

Case 4 – Surface Contaminated Object (SCO) – 1

Q4-1: *How this bucket should be transported?*

"Contamination" means the presence of a radioactive substance on a surface in quantities in excess of: 0.4 Bq/cm^2 for β, γ, and low-toxicity α emitters, or 0.04 Bq/cm^2 for all other α emitters. Since the bucket has been used with NORM (naturally occurring radioactive material), the α emitters will almost certainly be uranium and thorium decay products — low-toxicity α emitters. Therefore, the applicable limit is 0.4 Bq/cm^2.

Measured = 1 Bq/cm^2 > 0.4 Bq/cm^2 → Contaminated under ADR definition and fits SCO-I definition. Therefore, the bucket is considered a radioactive item for transport purposes.

Note: Even though only a small area (0.2 m^2) is contaminated, ADR considers any part exceeding the limit sufficient to classify as a radioactive item.

Implications for transport and servicing: Since the bucket is a radioactive item:

Transport: the bucket must be treated as a radioactive material for transport (**Class 7**). Depending on the activity/contamination, it may fall under:

- Exempted radioactive item: very small contamination and activity, limited external dose.
- Limited quantity or Type A: if higher activity.

Service/refurbishment: It cannot be sent to a standard workshop without complying with hazardous goods requirements. Whether the refurbishment facility must be registered or licensed to handle radioactive items or NORM-contaminated equipment depends on national regulations.

Case 5 – Surface Contaminated Object (SCO) – 2

Q5-1: How do you apply it if you have to decide on the status of several components that are radioactively contaminated at the surface?

a. *Both 0.4 Bq/cm^2 for beta and gamma emitters AND 0.4 Bq/cm^2 for low toxicity alpha emitters must be exceeded for classifying an item as contaminated?*

or

b. *0.4 Bq/cm^2 must be exceeded for the TOTAL of the beta and gamma and low toxicity alpha emitters for classifying an item as contaminated?*

The limits are per category of emitter, not cumulative for all categories combined. "Or" is inclusive for the two alpha categories: Low-toxicity alpha: 0.4 Bq/cm^2. Other alpha: 0.04 Bq/cm^2. Beta and gamma emitters have their own 0.4 Bq/cm^2 limit.

Hence, the answer to the question is:

a) "Both 0.4 Bq/cm^2 for beta/gamma AND 0.4 Bq/cm^2 for low toxicity alpha must be exceeded to classify as contaminated" → **incorrect**. You do not need both; exceeding any one of the relevant limits is enough.
b) "0.4 Bq/cm^2 must be exceeded for the TOTAL of beta/gamma and low-toxicity alpha" → also **incorrect**, because the ADR limits apply per radionuclide category, not as a sum.

In practice:

i) Staff member of a haulage company

Objective: Determine if a component qualifies as a "radioactive item" for transport.

1. Measure surface contamination per radionuclide category.
2. Compare each radionuclide category separately with the ADR limit.
3. If any exceed, classify the component as a radioactive item.
4. Apply Class 7 transport rules (packaging, labelling, documentation, dose control).

Key principle: Do not sum categories; treat limits separately.

ii) Consultant advising a private mining company

Objective: Minimize regulatory risk while ensuring safety.

1. Perform systematic surface contamination surveys per radionuclide type.
2. Compare with ADR limits for each category.
3. Recommend decontamination if any limit is exceeded, before transport or maintenance.
4. Provide advice on documentation, exemptions, and worker safety.
5. Apply conservative interpretation: treat any exceedance as contaminated.

Consultants should assume "worst case" contamination unless robust dose assessments are performed.

iii) Staff member of the competent authority

Objective: Verify regulatory compliance.

1. Check measurements and categories against ADR/UN limits.
2. Inspect documentation and confirm that any component exceeding a limit is classified and transported as a radioactive item.
3. Enforce packaging, labelling, transport, and worker protection requirements.
4. Ensure that the sum of contamination is not used incorrectly — limits are per category.

Authorities always apply a conservative, category-by-category approach.

9 COMMUNICATING ABOUT NORM

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9.1 Why do we need communication?

As radiation protection practitioners in industries involving NORM, we are dealing with a technical process. The process is carried out and maintained by people. These people have different responsibilities and roles. However, they must work together if radiation protection is to be successful. This requires a qualified and two-way communication for their realization.

9.2 Which roles do experts have in communication?

In section 1.2 we describe the ethical framework of communication and the different roles of experts, workers and members of the public. These roles are specified in relation to different levels of communication in Figure 9-1. The outcome of the Level 1 communication is the national regulatory system. In this handbook, we focus on the Level 2 to Level 4 communication.

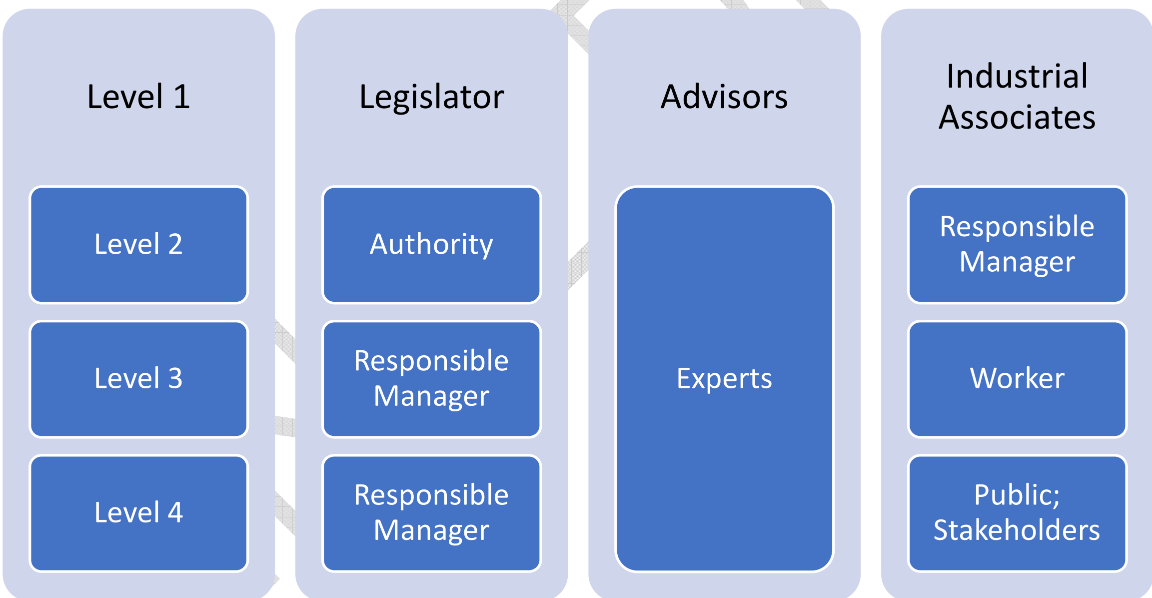


FIGURE 9-1: DIFFERENT LEVELS OF COMMUNICATION FOR RADIATION PROTECTION EXPERTS IN NORM RELATED PROCESSES

For the communication on Level 1 and Level 2, an equal or at least similar level of knowledge on radiation and radiation protection can be assumed. The communication can be focused on radiation protection, "RP". At Levels 3 and 4, the knowledge level is different. Therefore, emotions must be taken into account, and a significantly broader perspective on radiation protection is necessary. This broad perspective is part of a "**holistic approach**". As mentioned in Chapter 4, the chemical toxicity of components in NORM requires an integrated approach to protection and this should be considered in the communication with workers (Figure 9-2).

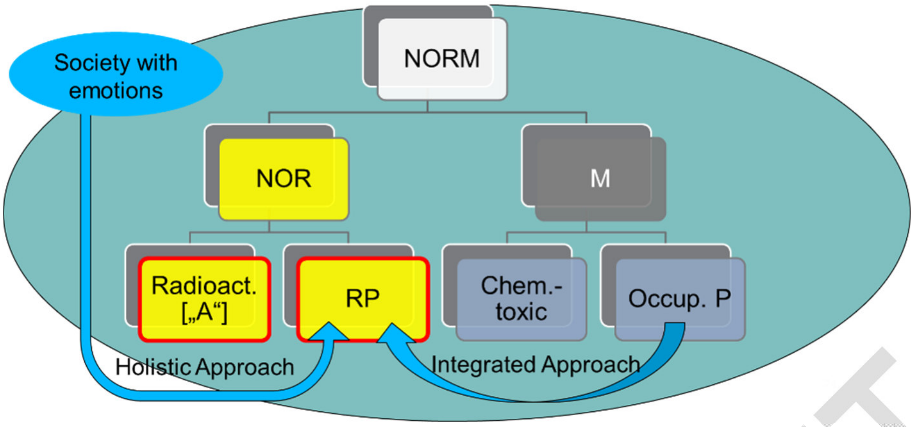


FIGURE 9-2: THE NORM-SYSTEM WITH INTEGRATED AND HOLISTIC APPROACH

BOX 9-1: FACTS ON NORM

- With NORM, there are no emergency exposure situations in which there is an immediate danger to life and limb from radiation. Communication in connection with NORM differs from the usual risk communication in radiation protection. It is not about informing the public in the event of radiological emergencies, where a concise and brief response to an exceptional emergency situation is required. Rather, it is about providing information or an assessment of chronic exposure at the workplace and in the environment, often at a low level of exposure.
- A particular problem is that members of our community for different reasons reflect on cancer risks that in many cases only exist at the level of everyday risks. There is no scientific evidence for cancer at doses of only few Millisievert per year. LNT does not reflects risks at low doses but is a tool for precaution and optimization!
- Despite LNT is a prudent but unproven approach there are many incantations in the scientific literature as well as public media that seek to construct dangers with reference to slight exceedances of the normal global averages published by UNSCEAR. The use of hazard indices (see Chapter 2) is also part of this narrative, which - conveyed via the public media - has become deeply engrained in the general consciousness.
- The public's unease about radiation is also rooted in such narratives of the expert community. As experts, we should stay away from this! As is usual in occupational safety, hazards should be named but not dramatized as long as there is no need to do so! There is no reason to stigmatize industries involving NORM because of radioactivity, there is no reason to stigmatize and thus prevent the disposal of NORM waste in a similar way.
- For NORM, radionuclides that are the sources of exposures are consistent with natural background and the worldwide background levels vary significantly.

9.3 How independent can experts be?

The experts involved in these communication processes usually work for one of the groups whose interests are to be realized in the communication process. The experts are obliged to act for their clients and are sometimes bound by instructions (e.g. as a public authority). Therefore, as experts, we are generally not always independent.

For honest communication, in possibly difficult proceedings, it is always important that the experts are aware of their role and how it is formalized and also perceived. It is very important to avoid portraying independence when that is not how the situation actually is. This would undermine the expert's credibility.

The value of an expert opinion is based on his/her professional expertise, which allows them to deliver clear messages into the discussion and the potentially difficult or conflicting environment.

When it comes to NORM, some fundamental facts should always be considered (see Box 9-1).

9.4 The IRPA-Approach to communications

The *IRPA Guidance on Engagement with the Public on Radiation and Risk* [164] provides a practical framework for communications that can be used for all forms of radiation exposure, including exposure from industries using NORM. While the focus of the document is on communication with the public, the key messages, methods and practical examples are equally applicable to other stakeholders, including workers and regulatory authorities.

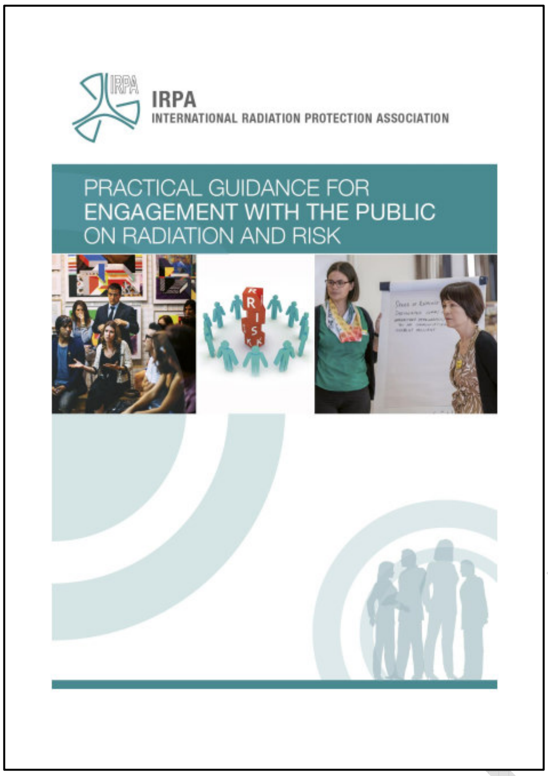


FIGURE 9-3: FRONTPAGE OF IRPA GUIDANCE [164]

This is best highlighted by the following statement from the guidance document:

Public understanding, trust and consent are absolutely central to implementing effective and proportionate radiation protection. Without this, we, as radiation protection professionals, will not fully achieve our aim of adequately protecting the public without unduly limiting the safe use of practical scientific and industrial practices for the benefit of mankind.

For the case of industries with NORM, this statement can be slightly modified to the following:

Public, worker, regulator and stakeholder understanding, trust and consent are absolutely central to implementing effective and proportionate radiation protection. Without this we, as radiation protection professionals, will not fully achieve our aim of adequately protecting the public without unduly limiting the safe use of practical scientific and industrial practices, and ensuring that resource use is optimized, for the benefit of mankind.

This chapter provides an overview of communication in general, based on IRPA guidance, with a focus on its application in industries with NORM.

Importantly, this chapter provides a number of practical examples, ideas and tips which have been used by members of the IRPA NORM Task Group. Remember that "one size does not fit all" and some of these will work in your situation and some will not.

The IRPA Communication Guidance says;

"People need to know that you care, before they care about what you know."

This is probably the most important principle of communication. It means that emotions are crucial, especially when communicating with the public. You should always remind yourself of this when you are doing any communication with laypersons of the public. When communicating with workers, e.g. to explain instructions, factual information is more important and when communicating between authorities and managers of private companies, the factual level is dominant.

Therefore, clarity on your role in the field of interests is needed.

9.5 How to communicate with the authorities

Communication between authorities and responsible managers of industrial companies is vitally important for balanced workers and environmental protection and for the business operations. A co-operative approach by companies and authorities requires respect that should take into account the actual potential radiological risks, which are usually rather low.

The authorities are usually represented by a range of qualified people, including lawyers, environmental engineers, managers and radiation protection experts. They have their own resources for control, inspection and measurements.

From an industry perspective, in many cases, the responsible managers are laypersons in radiation protection. They need experts (Advisors, consultants or qualified employees) for effective technical communication with the authorities.

On this level, the communication is mainly about the legal requirements (such as licensing) and appropriate implementation of the requirements in an operational radiation protection system.

The role of experts is to assist in understanding the technical risks and providing advice on appropriate control measures and finding the balance between the regulatory requirements and the operations company requirements.

This level of communication is less influenced by emotions. Communication about radiation risks is not decisive. This does not mean that we have to gloss over the radiation risks. We simply have to put them in relation to other risks and endeavor to deal with them objectively in our communication.

9.6 How to communicate with workers?

The challenge in communication with workers is to generate awareness that consists of following the measures given by the radiation protection regulations, accepting legal requirements and handling radioactively contaminated materials sensibly. It is primarily about information and not too much about warning.

Instructions are a typical form of communication with workers. For these instructions to be understood and accepted by employees, they must be tailored to the work in question and the potential risks involved. For radiation protection, this means that all essential information/data about the work and the occurring exposure pathways must be gathered/collected. On this basis, dose estimates can be carried out before work begins, if necessary, and control measurements can be carried out for routine work. The factual and risk-appropriate assessment of the doses determined in this way is the second element that is needed for a case specific instruction. Radiation risks and emotions play a role but are frequently not decisive if the messages are clearly presented.

In any routinely operated process, the communication with workers should not be a single instruction, but a regular process. The cycle of data collection, assessment and communication (CAC-Cycle, see Figure 9-4) is one of the possibilities of optimization.

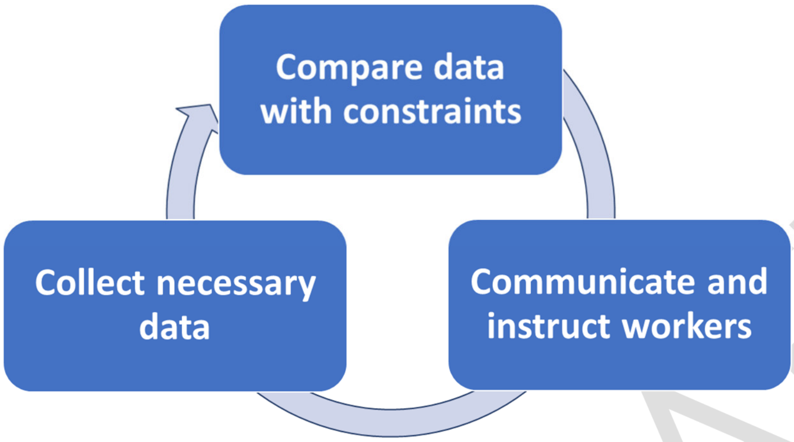


FIGURE 9-4: COMMUNICATION AS THE KEY FOR OPTIMIZATION IN RP OF NORM: THE "CCC-CYCLE"

Commonly, instructions in radiation protection are only one part of many safety instructions of miners or industry workers. Some examples of instructions are given in Chapter 9.11.

9.7 How to communicate with the public?

Most people in the community are influenced by social media, the mainstream media and popular culture and have images in their mind about radiation and its impacts. It is important to note that our primary task as practitioners is not to seek to change people's minds and perceptions about radiation. It is to respect their views and provide clear and concise information and data so that they can make their own decisions. Too often, various groups or individuals try to change people's minds, and this is not our role.

Doing this well means that we also need to manage our own perceptions when we communicate.

It is true to say that the complexity of the system and protection, and the science and philosophy that it is based on, is a barrier to effective communications and it is the interpretation and practical implementation of the system that generates many of the difficulties. An easy and well-communicable system is required to prevent prejudices from adversely affecting industrial activities or otherwise resulting in inadequate radiation protection.

Practitioners are often confronted with issues arising from prejudices, views and opinions of people on radioactivity and ionizing radiation. These issues arise, for example, when workers first learn of radioactivity in their personal workplaces or when local residents learn of radioactivity at an industrial plant in their neighborhood. Similarly, when commercial consumers learn of radioactivity in products, there is concern. In all these cases the complex system of radiation protection needs to be interpreted consistently because the radiological risks of

NORM tend to always be outweighed by other risks. However, decisions are frequently made based on emotions and various inconsistent interpretations of the system of protection.

An important role of the practitioner is to contribute to broader decision making with the aim of ensuring that an economically and socially beneficial activity is not unnecessarily constrained due to the perceived risks of radiation.

As noted previously, it is important to ensure that a practitioner should not be seen as an advocate of a particular activity. They should be considered to be a trusted source of advice, knowledge and information that is used in the broader decision making.

The exception to this rule, is when there may be an identified and proven immediate safety and environmental risk from an activity, and then the practitioner must have the courage and ability to intervene.

9.8 How to communicate with consumers, buyers, users?

As already mentioned in Chapter 3, materials with increased natural radioactivity are also marketed and sold as products. Typical products are zirconium-containing refractory materials, abrasives and foundry additives. Furthermore, thoriated tungsten electrodes and other thermally highly stressable components made of thoriated tungsten or thoriated magnesium are used. Potash salts and mixtures that contain a significant share of potash salt are a special case.

To communicate about the radioactivity of such products **Safety Data Sheets** are a good option. Safety Data Sheets are attached to the sales documents in order to inform the users, who are generally professionals, about possible hazards. These sheets contain information on all hazardous chemical substances. Information on radioactivity is not mandatory. However, they such additional information is useful for providing an explanation of the cause of radiation alarms at measuring systems at border crossings or international harbors. The same applies to customers who are suddenly confronted with the issue of radioactivity in a product and do not have an overview of the resulting radiation protection issues.

The shortest way of letting the users know about the radioactivity is a brief statement like "This product contains uranium and thorium which are radioactive elements", or "This product contains naturally occurring radioactivity". By such a message, the user is generally informed and has to ask the supplier if he/she need more information.

A more comprehensive method is **specific certificates**. Such certificates may be added as an annex to a Safety Data Sheet or delivered separately. Their content should cover for at least

- Name of the product
- Purpose of use
- Data on activity concentrations,
- A statement on the assessment of the data referred to international standards (1 Bq/g uranium or thorium decay series radionuclides; 10 Bq/g K-40)

More qualified certificates contain additional:

- Statements on measuring techniques, the responsible laboratory, and data on measuring uncertainties.

- Statements on the assessment of the measuring results referred to national standards in the country of the recipient and user (including information on exemption from regulations for small quantities)
- A statement on the classification according to the hazardous good transport regulations. This does not exempt you from proper signage and labelling when transporting dangerous goods (see Chapter 8).
- Some general comments on radiation protection (avoid dust inhalation, do not stay near the product if not necessary)

In individual cases the certificates the following information may be added, too:

- Generic estimations of doses for workers using the product.
- Data on measurable dose rates at packages or truck loads.

Advanced certificates are adopted not only to the national laws but also to the national language of the customers!

The more and better information the producer provides, the lower the risk of subsequent complaints or even liability claims.

9.9 Being clear when communicating

In radiation protection, there is a range of terms that are used when working with and when communicating about radiation. For professionals engaged in the field, these terms are commonly used and sometimes mis-used when the interpretation of the terms and their application is different. This results in difficulties when communicating with people outside the profession, such as the public, and is both a barrier to effectively delivering any messages and can undermine the intent of the message being delivered. Another layer of complexity arises when words or terms are translated into different languages, which again results in different interpretations of the terms.

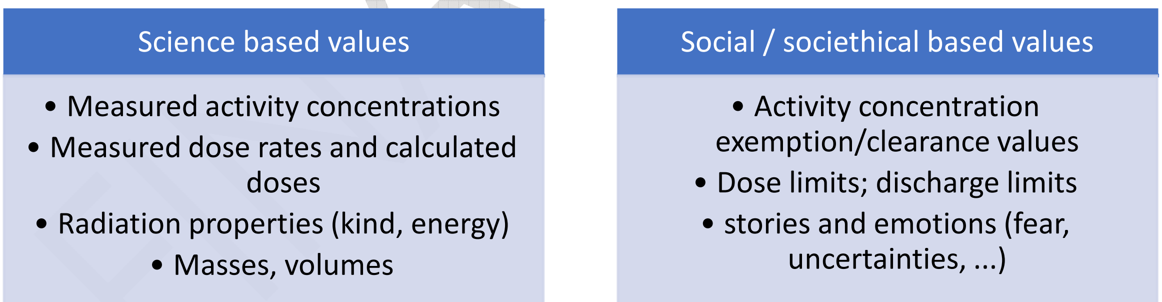


FIGURE 9-5: CONSIDER DIFFERENT TYPES OF VALUES IN COMMUNICATION

Examples, where terms are interpreted in different ways, include:

- Practical application of the terms, such as, "limit", "constraint" and "reference levels". While the terms are sometimes used interchangeably, more importantly, in some situations, they are seen to have the same meaning.
- Inconsistent use of the term NORM itself. IAEA recommends using this term only if naturally occurring radioactive materials are under a regulatory regime, but the term is also

applied to all materials that contain natural radionuclides. In the latter case, NORM becomes part of the background.

- Consideration of the impacts of background radiation. Background radiation levels vary around the world and depend upon a range of factors. Because "genuine" background radiation is not amenable to control, it is excluded from radiation protection. Consequently, radiation risks in radiation protection refer to additional doses to a variable background. But in communication with the public, the doses from this background are used for comparison purposes. Moreover, in the case of radon, the background is included in the risk assessments as far as activity concentration is used for radiation protection.
- Equating the terms NORM, nuclear and radioactivity. In practice, the terms NORM nuclear and radioactivity are used interchangeably. In some situations, this is actually formalized in legislation where, in some situations, NORM facilities are classified as nuclear facilities. Unclear whether NORM is dangerous.

A primary requirement for any practitioner is to be clear in what they are communicating and to be precise in the use of terms.

9.10 Which difficulties should be considered?

With NORM, there are no emergency exposure situations in which there is an immediate danger to life and limb from radiation. Communication in connection with NORM differs from the usual risk communication in radiation protection. It is not about informing the public in the event of radiological emergencies, where a concise and brief response to an exceptional emergency situation is required. Rather, it is about providing information or an assessment of chronic exposure at the workplace, often at a low level of exposure.

A particular problem is that sometimes, members of our community, for different reasons, reflect on cancer risks from NORM. In almost all cases, the potential cancer risks are the same as those occurring in everyday risks. There are many such examples in the scientific literature that seek to "construct" dangers with reference to slight exceedances of the normal global averages published by UNSCEAR. The formal use of hazard indices (see Chapter 2) is also part of this narrative, which - conveyed via the public media - has become deeply engrained in the general consciousness. The public's unease about radiation is also rooted in such narratives of the expert community.

As professionals, we should be very careful about the messages that this sends and the impacts it may have!

As is usual in occupational safety, hazards should be identified but not dramatized if there is no need to do so. There is no reason to stigmatize NORM industries because of radioactivity, which is but one of the many hazards and risks that are present. This is similarly the case for NORM waste.

There are other basic principles for the good communications, and these include:

- Ensuring that the risks and benefits are spoken about. In the case of NORM, the benefits are better use of resources, jobs, access to higher technologies, while the radiological risks are relatively low and well known.

- An individual's perception is true to them, and therefore it is not incorrect in their mind. It is important to respect this.
- Consider both the costs and benefits of a situation when discussing risks.
- Prepare any communications strategy in advance and have frequently asked questions and answers prepared. Use visual methods, such as monitoring equipment.
- Be a clear, authorities and confident speaker. If you have doubts about your speaking skills, then seek some training.
- People's perceptions will not usually be changed by mere presentation of facts and information. People's perceptions are more likely to change when they trust the kind of presentation.
- It is OK not to know an answer to a question. It is better to say "Please allow me to get back to you on that question" rather than making up an unsatisfactory answer. Of course, it is cortical that you do get back to the person or the group who asked the question.
- When communicating, make sure that you understand the full picture. For example, where the NORM material is coming from, how it will be processed, what it will be used for. This assists in communicating a broader understanding of the situation.
- Be clear about what is an unacceptable risk and be prepared to use the word "safe" if you are comfortable to do so.
- Always have simple clear messages that can be elaborated on when required.

9.11 NORM communication examples

This section provides a number of tips, examples and ideas for communicating radiation risks with NORM. Earlier in this chapter, it was noted that the IRPA Communications Guidance document provides some core principles that should always be applied when communicating.

<u>Communicating with workers</u>

An example of an instruction is shown in Box 9-2.

Based on practical experience we state:

- Managers ensure that radiation training is provided for workers as part of the established health and safety program, highlighting that radiation is one of a number of hazards in the workplace.
- Workers need to understand the activities that they are involved with, what measures to take to protect themselves, members of the public and to ensure no contamination of the environment.
- Apply proactive management, where managers understand the broad range of hazards and risks and also have characterized any radiological risks.
- Staff should have access to qualified practitioners rather than relying on less reliable informal methods, such as social media.
- Many larger companies have a formal risk management process which help to decide what risks are "acceptable" and those that require mitigation. Having "radiation" as one of the risks dimensions is an important way of ensuring management focus.

Practical example from Nederlandse Aardolie Maatschappij (NAM)

All activities at NAM production sites with a potential exposure to NORM are supervised by trained Radiation Protection Supervisors (RPS). These RPS ensure that the workers on site are sufficiently informed about NORM. As part of a Safety Information Booklet which is shared with all workers (including contractors), a very condensed information about NORM is given (see Figure 9-6).

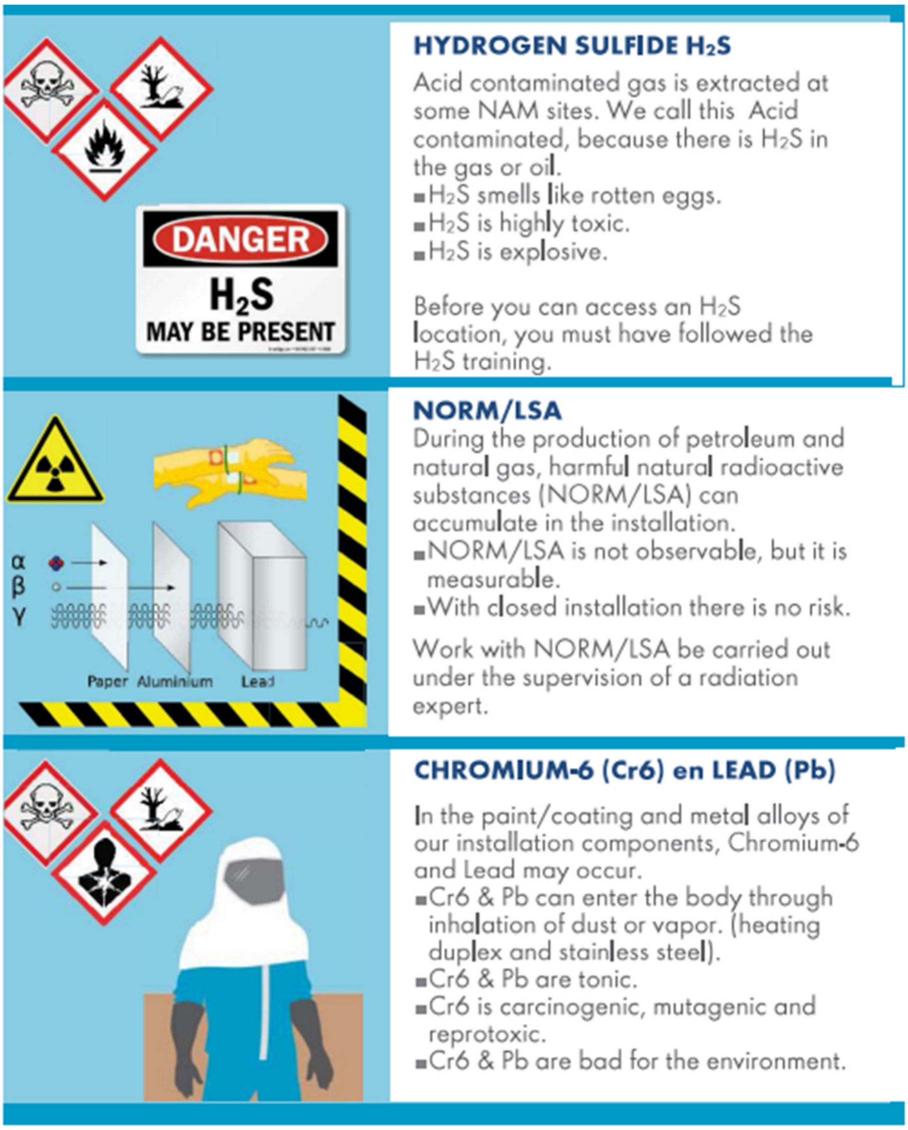


FIGURE 9-6: INFORMATION LEAFLET ON NORM AND CHEMICAL HAZARDOUS SUBSTANCES USED BY NEDERLANDSE AARDOLIE MAATSCHAPPIJ (NAM)

BOX 9-2: EXAMPLE: INSTRUCTION FOR WORK ACTIVITIES WITH RARE EARTH ORES (REE ORES)

Occasion and general conditions
- When working with rare earth ores (REE ore), appropriate safety measures must be observed regarding possible radiation hazards, about which employees must be instructed on record before commencing work. The instruction shall be given by the responsible radiation protection officer.
- The instructions must be complied with to prevent health hazards. These are only protective measures regarding the increased radioactivity and not regarding the hazards that may arise from the activities themselves. Instructions regarding latter are not included in the following explanations.
- If women of childbearing age are involved in activities with REE ores, it is pointed out that a pregnancy must be reported as early as possible in view of the risks of exposure for the unborn child and that contamination by dust from REE ores can lead to internal exposure of an unborn or breastfed child.
- The company keeps the Radiation Protection Act and the Radiation Protection Ordinance available for further information on the legal regulations.

General provisions
- Work must be carried out in compliance with the usual accident prevention and occupational protection provisions.
- The generally applicable rules of hygienic behaviour must be observed. Eating, drinking, smoking, the use of snuff, chewing gum and cosmetics as well as health care products are prohibited.
- After leaving, the usual personal hygiene measures such as hand washing must be carried out.

Access regulations
- The work areas must be demarked.
- Access to the work areas shall be controlled during working hours by the responsible person.
- Unnecessary stays in the work areas must be avoided.

Personal protective equipment and behaviours
- Persons who constantly work with REE ores are equipped with appropriate protective clothing and personal dosimeters. They are obliged to wear the dosimeters on their chest outside their clothing.
- The following personal protective equipment (PPE) must be used
  - Closed safety shoes
  - Eye protection
- The following personal protective equipment (PPE) must be used if required or when instructed to do so:
  - Protective gloves (when direct contact to REE ores or contaminated surfaces is possible)
  - Respirator mask (FFP3, when dust may occur).
- During the work, care must be taken to ensure that contamination of the body and incorporations are safely prevented by effective PPE. Only PPE that is in perfect, functional condition may be used.

Avoiding the spread of contamination
- Before leaving the work areas, the soles of shoes must be cleaned or, if necessary, shoes must be changed to prevent the spread of contamination to the outside. If necessary, contaminated protective clothing must be removed after visual assessment before leaving the work areas. Contaminated protective clothing must be collected in suitable containers (e.g. containers with lids).
- Contaminated objects (e.g. tools, other equipment, etc.) must also be cleaned within the work areas.
- When driving on the work areas with work machines or vehicles, adhesion of contaminated material to the tyres / wheels cannot be ruled out. Tyres/wheels must therefore be checked for contamination and cleaned. Contaminated material must be prevented from being carried out of the work area. The driver's cabs must be cleaned every working day. Avoid dragging contaminated material into the driver's cabs with footwear.
- Personal items (e.g. bags, jewellery) must not be taken into the work areas.
- Dust formation must always be reduced as far as possible and, if necessary, prevented by suitable measures (light moistening, extraction).

Behaviour in case of suspected incorporation
- If incorporation is suspected, activities must be stopped immediately, and the responsible manager must be informed.
- The person concerned must be removed from the work area. If necessary, a doctor must be consulted.

Behaviour in the event of accidents and disruptions to operations
- Accidents or incidents involving the release of contaminated material cannot be compared with incidents in plants with artificial radionuclides. Due to the relatively low specific activity of the materials, no situations arise in which an acute hazard situation can occur for radiological reasons.
- Situations that may need to be considered are accidents in which heavy dust formation may occur temporarily. However, as clean-up work after such an incident takes a short time, the use of PPE rules out the possibility of the body doses of the employees involved exceeding the effective dose value of 1 mSv/a. Therefore, immediate radiation protection measures in the event of an accident in the work area are not necessary.

The common actions in such cases must be done:
- Rescue: Remove persons from the immediate danger zone. Remove injured persons from the danger zone, observing the principles of self-protection and first aid.
- Inform: Responsible manager, accident physician, and fire brigade, if necessary
- Make safe: Interrupt activities in the danger zone. Close off the danger zone for access
- Go to the assembly point and do not leave without the consent of the responsible person.

Confirmation
The instructed persons confirm that they have understood all the contents of the instruction. The instructed persons undertake to always comply with the contents of this instruction.

Communicating with the regulatory authority

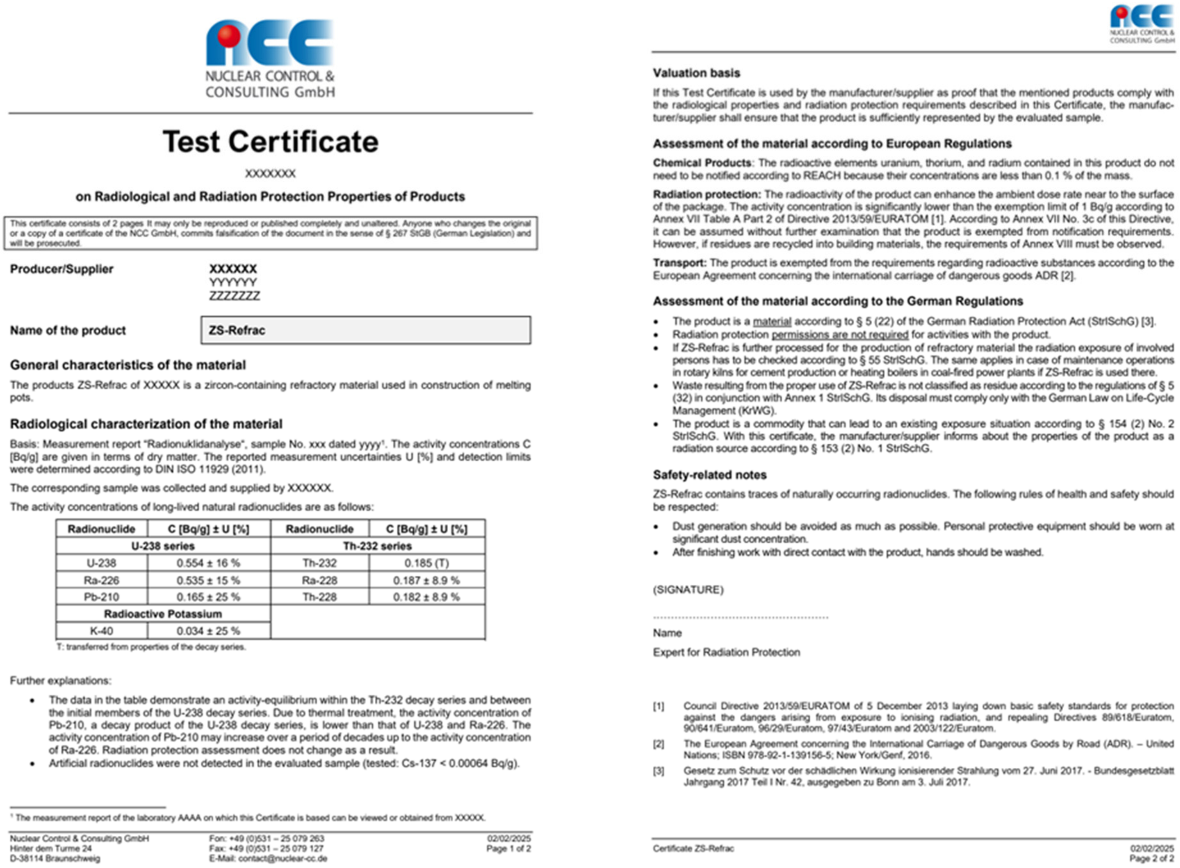
- As noted elsewhere in this document, a good working relationship between the regulator and the operator goes a long way to improving radiological outcomes. A positive working relationship, rather than an adversarial relationship, is always more beneficial.
- A communications role in some countries is undertaken by the regulator. However, it is the responsibility of the operator to understand and manage their hazards and risks. Therefore, the company can provide data so that the regulator is able to effectively communicate.
- This requires collaboration between regulators and the operators, and, for example, this can be formalized through a memorandum of understanding.

Communicating with the public

- There are many different examples of methods to communicate with the public and due to the different requirements across areas, there is no one project that fits all. Usually, it is identifying what works in the particular area and adapting and applying.
- Provide talks in schools, and explaining the radioactive world we live in, including natural background. In some situations, providing students with monitoring equipment as school experiments.
- For companies, good communications can be established with the public, but having open days or engaging in school projects, where students might learn more about the operation and undertaken activities, such as small monitoring experiments. (Note that for these activities, it is important to ensure the safety of all involved.)
- Providing information that man-made radiation is different NORM mainly because man-made radiation is for specific purposes and usually exposures are much higher than for NORM. This is a difficult concept to get across.
- Sometimes people just do not trust the company, the regulator or the technical services provider. Therefore, an alternative is to engage people who have a higher level of trust, for example doctors, or community leaders. An example includes forming a consultative group including community leaders and community members.

Communication with (professional) consumers

- Companies that use products classified as NORM should be made aware of the radioactivity in the products as part of the usual product information (e.g. in safety data sheets).
- In order to communicate transparently and openly from the outset, information on the radioactivity of the products and notes on the legal assessment can be provided in separate information sheets. An example of such a sheet of a German producer is shown in Figure 9-7.



NUCLEAR CONTROL & CONSULTING GmbH

Test Certificate

XXXXXXX

on Radiological and Radiation Protection Properties of Products

This certificate consists of 2 pages It may only be reproduced or published completely and unaltered. Anyone who changes the original or a copy of a certificate of the NCC GmbH, commits falsification of the document in the sense of § 267 StGB (German Legislation) and will be prosecuted.

Producer/Supplier XXXXXX
YYYYYY
ZZZZZZZ

Name of the product **ZS-Refrac**

General characteristics of the material

The products ZS-Refrac of XXXXX is a zircon-containing refractory material used in construction of melting pots.

Radiological characterization of the material

Basis: Measurement report "Radionuklidanalyse", sample No. xxx dated yyyy[1]. The activity concentrations C [Bq/g] are given in terms of dry matter. The reported measurement uncertainties U [%] and detection limits were determined according to DIN ISO 11929 (2011).

The corresponding sample was collected and supplied by XXXXXX.

The activity concentrations of long-lived natural radionuclides are as follows:

Radionuclide	C [Bq/g] ± U [%]	Radionuclide	C [Bq/g] ± U [%]
U-238 series		Th-232 series	
U-238	0.554 ± 16 %	Th-232	0.185 (T)
Ra-226	0.535 ± 15 %	Ra-228	0.187 ± 8.9 %
Pb-210	0.165 ± 25 %	Th-228	0.182 ± 8.9 %
Radioactive Potassium			
K-40	0.034 ± 25 %		

T: transferred from properties of the decay series.

Further explanations:

- The data in the table demonstrate an activity-equilibrium within the Th-232 decay series and between the initial members of the U-238 decay series. Due to thermal treatment, the activity concentration of Pb-210, a decay product of the U-238 decay series, is lower than that of U-238 and Ra-226. The activity concentration of Pb-210 may increase over a period of decades up to the activity concentration of Ra-226. Radiation protection assessment does not change as a result.
- Artificial radionuclides were not detected in the evaluated sample (tested: Cs-137 < 0.00064 Bq/g).

[1] The measurement report of the laboratory AAAA on which this Certificate is based can be viewed or obtained from XXXXX.

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02/02/2025
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NUCLEAR CONTROL & CONSULTING GmbH

Valuation basis

If this Test Certificate is used by the manufacturer/supplier as proof that the mentioned products comply with the radiological properties and radiation protection requirements described in this Certificate, the manufacturer/supplier shall ensure that the product is sufficiently represented by the evaluated sample.

Assessment of the material according to European Regulations

Chemical Products: The radioactive elements uranium, thorium, and radium contained in this product do not need to be notified according to REACH because their concentrations are less than 0.1 % of the mass.

Radiation protection: The radioactivity of the product can enhance the ambient dose rate near to the surface of the package. The activity concentration is significantly lower than the exemption limit of 1 Bq/g according to Annex VII Table A Part 2 of Directive 2013/59/EURATOM [1]. According to Annex VII No. 3c of this Directive, it can be assumed without further examination that the product is exempted from notification requirements. However, if residues are recycled into building materials, the requirements of Annex VIII must be observed.

Transport: The product is exempted from the requirements regarding radioactive substances according to the European Agreement concerning the international carriage of dangerous goods ADR [2].

Assessment of the material according to the German Regulations

- The product is a material according to § 5 (22) of the German Radiation Protection Act (StrlSchG) [3].
- Radiation protection permissions are not required for activities with the product.
- If ZS-Refrac is further processed for the production of refractory material the radiation exposure of involved persons has to be checked according to § 55 StrlSchG. The same applies in case of maintenance operations in rotary kilns for cement production or heating boilers in coal-fired power plants if ZS-Refrac is used there.
- Waste resulting from the proper use of ZS-Refrac is not classified as residue according to the regulations of § 5 (32) in conjunction with Annex 1 StrlSchG. Its disposal must comply only with the German Law on Life-Cycle Management (KrWG).
- The product is a commodity that can lead to an existing exposure situation according to § 154 (2) No. 2 StrlSchG. With this certificate, the manufacturer/supplier informs about the properties of the product as a radiation source according to § 153 (2) No. 1 StrlSchG.

Safety-related notes

ZS-Refrac contains traces of naturally occurring radionuclides. The following rules of health and safety should be respected:

- Dust generation should be avoided as much as possible. Personal protective equipment should be worn at significant dust concentration.
- After finishing work with direct contact with the product, hands should be washed.

(SIGNATURE)

....

Name

Expert for Radiation Protection

[1] Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom.

[2] The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). – United Nations; ISBN 978-92-1-139156-5; New York/Genf, 2016.

[3] Gesetz zum Schutz vor der schädlichen Wirkung ionisierender Strahlung vom 27. Juni 2017. - Bundesgesetzblatt Jahrgang 2017 Teil I Nr. 42, ausgegeben zu Bonn am 3. Juli 2017.

Certificate ZS-Refrac
02/02/2025
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FIGURE 9-7: EXAMPLE OF AN INFORMATION SHEET ABOUT RADIOACTIVITY OF A REFRACTORY PRODUCT

9.12 Other Practical Tips When Communicating

Here are some other practical tips for communicating.

- Start communicating and engaging early in a project, or even before the project starts, even if the project does not proceed.
- When delivering training, it is important to engage with the trainees. Merely delivering a lecture is easy, but not usually effective. Take the time to answer questions and understand why questions are asked, and any underlying key issues. Allow trainees to discuss matters and most important of all, allow them to be free to make informed decisions.
- Use practical and hands-on demonstrations when talking about radiation. For example, have some monitoring equipment and allow people to handle and use the equipment. If you are providing a presentation on behalf of a company, have some of the material being produced (if it is radioactive) and show attendees the results using monitoring equipment.
- Many countries have radiation protection practitioner societies. For example, the UK has the Society for Radiological Protection which has a number of outreach programs and also a schools resources page which includes lesson plans and posters.

Other communication ideas and programs

- Companies can provide information on their operation, which can include communications via their website, media interviews, face to face meetings. In these cases, it is important that the regulator maintains transparency via licensing and ongoing regulation. This can be done through providing information on their website.
- Where an activity or operation is licensed for the purposes of radiation protection, there is usually a requirement on the operator to develop a radiation management function. Through this function, radioecological risk is assessed and monitored. This provides information for communication to the workers or the public. In addition, the program generally requires that workers undergo training.
- There are many other professional disciplines who influence the discussion on radioactivity, including lawyers, teachers, engineers and communications experts. People form these professions bring their own views on radiation, so actively interacting, educating and informing other disciplines is an important for improving communications.
- Industry organizations have an important role in communicating the facts about the industry. While it might be seen to be "biassed", the organizations should be clear on the hazards and risks and the benefits and offer alternative sources of information for people to make informed decisions.

Additional discussions on radiological protection and the public are given in [165].

10 What products and consumer goods contain NORM?

Authors: Stephane Pepin

Contributors: Anne Cordelle, Rainer Gellermann, Jeakook Lee

10.1 Introduction

As already mentioned in Chapter 3, at the end of the industrial production chain (Figure 3-1), products that contain NOR and can be considered NORM in specific cases (fertilizers, ceramic tiles, refractory bricks, etc.) are traded and used for their intended purposes. In most cases, however, the use of these products is not related to the radioactive properties of the natural radioactive substances they contain.

This chapter provides information on these products and the RP framework designed for them. However, the term *product* is highly generic, and similar terms such as *goods* and *commodities* carry very similar meanings. Moreover, the product of a given industrial activity may serve as a raw material for another. Therefore, this chapter discusses terminology issues related to NOR-containing products and proposes definitions for each term. We try to address the different contexts where NOR-containing products may appear:

- The intentional use of natural radioactive chemical compounds in the manufacturing of a product: e.g., thorium welding electrodes, uranium oxide used as a pigment in ceramics (Figure 10-1) or glasses, etc.
- Products containing NOR as a contaminant or as part of its natural composition (potassium compounds);
- Legacy products, such as the many objects where radium was used for its radioactive (radioluminescent) properties;
- Products used in industrial processes and products directly used by members of the public;
- Products where enhanced natural radioactivity is inadvertently discovered through, e.g., portal monitor detection.
-

Additionally, it presents methods for identifying NORM products in trade and conducting radiation monitoring procedures. It addresses the regulatory context and provides two case-studies illustrating a possible regulatory process for some of these products. Finally, it also mentions the special case of potassium-based products.

FIGURE 10-1: U-GLAZED TILES ON A PRIVATE HOME IN BRUSSELS (BELGIUM).

Note: Similar tiles may be found e.g. at the metro station Rosenthaler Platz in Berlin and in many other public buildings in the world.

10.2 Terminology issues

The terms *raw material* and *product* are conceptually distinct in a dictionary sense: generally, raw materials refer to substances used in the production of products, whereas products are materials resulting from a manufacturing process. However, the boundary between these two concepts is not clear-cut: products of a given manufacturing process are often used as raw material for another process. For instance, phosphoric acid is a product of phosphate processing, but it is also a raw material in the production of soft drinks or other food products. Potassium chloride is a product of a manufacturing process and may be used by end consumers as a salt substitute or regarded as a raw material for the production of other chemicals.

Therefore, for the sake of this chapter, we limit the scope to products that undergo no further processing and are directly used by the final consumer. It may be an industrial use, such as the use of refractory bricks in an industrial oven, or other building material, or thorium-welding electrodes in a factory, etc. Or it may be private use by the general public, such as ceramics, jewelry, foodstuffs, etc.

Other terms, such as *consumer products*, *consumer goods*, and *commodities,* are commonly used to refer to products. The issue of terminology is also addressed in IAEA discussion document "*Radioactivity in Goods Supplied for Public Consumption or Use: Towards an Internationally Harmonized Regulatory Framework*" [1]. Only the term *consumer products* is explicitly defined in the IAEA Safety Glossary:

Consumer product (Reference: IAEA Safety Glossary)

A device or manufactured item into which radionuclides have **deliberately** been incorporated or produced by activation, or which generates ionizing radiation, and which can be sold or made available to members of the public without special surveillance or regulatory control after sale.

Consumer products include items such as smoke detectors and luminous dials into which radionuclides have deliberately been incorporated and ion generating tubes. It does not include building materials, ceramic tiles, spa waters, minerals, and foodstuffs, and it excludes products and appliances installed in public places (e.g., tritium exit signs).

There are two important aspects of this definition:

- the incorporation of radionuclides in the product is **deliberate**;
- the product is made available to members of the public **without special surveillance**.

Consumer goods are a broader term that refers in general to goods made available to the general public. The IAEA discussion document [1] proposes the following definition:

"***Consumer goods are those products supplied for public consumption or use, including merchandise, edible and non-edible commodities, and other materials, goods or articles***".

The term <u>*Commodities*</u> is even broader and has rather an economic meaning of "something which is traded": it may be a raw material, a product, foodstuffs, etc.

Although the term "commodities" is used in IAEA BSS, it is not defined in the IAEA Safety Glossary. ICRP Publication 104, however, has used the term commodity with the meaning of "*products generally used or consumed by the public, such as foodstuffs and building materials, [that] can contain radioactive substances*". As pointed out in [1], this definition differs from the common meaning of the term commodity, which denotes a raw material or primary agricultural product that can be bought and sold, such as on the commodities markets.

As we will see in this chapter, these various terminologies and definitions may create confusion among the radiation protection community and the public. As a result of this confusion, regulatory requirements applicable to consumer products may sometimes be applied to other commodities that do not fall under the definition of consumer products.

Box 10-1 summarizes the definitions of the different terms: consumer products (from IAEA Safety Glossary), commodities, consumer goods, and goods (from Oxford dictionary).

Box 10-1: Terms **Consumer product (**Reference: IAEA Safety Glossary) A device or manufactured item into which radionuclides have deliberately been incorporated or produced by activation, or which generates ionizing radiation, and which can be sold or made available to members of the public without special surveillance or regulatory control after sale. Consumer products include items such as smoke detectors and luminous dials into which radionuclides have deliberately been incorporated and ion generating tubes. It does not include building materials, ceramic tiles, spa waters, minerals and foodstuffs, and it excludes products and appliances installed in public places (e.g. tritium exit signs).
Commodity (Reference: Oxford English Dictionary); https://www.oed.com/dictionary/commodity_n?tab=meaning_and_use#8753153) 3.a. A natural resource, material, etc., which is of use or value to humankind; a useful product. Frequently in plural. 3.b. A thing produced for use or sale; a piece of merchandise; an article of commerce; in later use frequently spec. a raw material, primary product, or other basic good which is traded in bulk and the units of which are interchangeable for the purposes of trading.
Consumer good (Reference: Oxford English Dictionary; https://www.oed.com/dictionary/consumer-goods_n?tab=meaning_and_use&hide-all-quotations=true#132043063100 Goods bought and used by consumers (opposed to producer goods); also in singular. **"Good"** (Reference: Oxford English Dictionary) https://www.oed.com/dictionary/good_adj?tab=meaning_and_use&hide-all-quotations=true#2860496 III. A particular thing that is good or beneficial. III.10.a. Things that are produced for sale; commodities and manufactured items to be bought and sold; merchandise, wares; (in Middle English) spec. crops; produce. Now also (Economics): economic assets which have a tangible, physical form (contrasted with services).

In the current definition of *consumer product*, the most critical criterion is whether radionuclides are *deliberately added*, while the intended use of the product is not a major distinguishing factor. As a result, both *Am-Be smoke detectors*, which utilize radiation effects, and *thorium welding rods*, which do not, are categorized as *consumer products*.

10.3 Regulatory context: consumer products and commodities in IAEA requirements

Consumer products are addressed explicitly in requirement 33 of IAEA BSS:

"Providers of consumer products shall ensure that consumer products are not made available to the public unless their use by members of the public has been justified, and either their use has been exempted or their provision to the public has been authorized."

According to requirement 3, production, supply, provision, and transport of consumer products are subject to the requirements for planned exposure situations. Requirements regarding consumer products are further detailed in IAEA Specific Safety Guide 36 [3]. Regarding justification, requirement 3.17 considers the following practices to be not justified:

a) *Practices,…, that result in an increase in activity, by the deliberate addition of radioactive substances or by activation, in food, feed, beverages, cosmetics or any other commodity or product intended for ingestion, inhalation or percutaneous intake by, or application to, a person;*
b) *Practices involving the* <u>*frivolous use of radiation*</u> *or radioactive substances in commodities or in consumer products such as toys and personal jewellery or adornments, which result in an increase in activity, by the deliberate addition of radioactive substances or by activation*.

This forms the basis for the prohibition of many past uses of radionuclides, especially radium, in cosmetics or on watches, measuring instruments or toys.

Regarding <u>natural radionuclides in commodities</u>, IAEA BSS rather considers it as an existing exposure situation:

> *Requirement 5.1 The requirements for existing exposure situations in Section 5 apply to:*
>
> *… Radionuclides of natural origin, regardless of activity concentration, in commodities, including food, feed, drinking water, agricultural fertilizer and soil amendments, and construction materials, and residual radioactive material in the environment;*
>
> Requirement 51 addresses exposure due to radionuclides in commodities and requires the establishment of a reference level:
>
> *...The regulatory body or other relevant authority shall establish specific reference levels for exposure due to radionuclides in commodities such as construction materials, food and feed, and in drinking water, each of which shall typically be expressed as, or be based on, an annual effective dose to the representative person that generally does not exceed a value of about 1 mSv.*

When implementing IAEA requirements in practice, the absence of a clear definition of commodities and the thin line between the concept of consumer products and the concept of commodities may be a source of confusion. It is not necessarily clear which requirement needs to be applied (for instance, regarding justification: see Chapter 2 and Chapter 4) In particular, the meaning of "*deliberately incorporated radionuclides*" may in some cases be ambiguous.

The addition of uranium oxide as a pigment in the manufacture of ceramics glazed-tiles to give them a bright orange color, is obviously a "deliberate incorporation" of radionuclides, but is the addition of zirconium oxide in the manufacturing process of glazed-tiles a "deliberate addition of radionuclides" knowing that zirconium oxide contains traces of uranium with an activity higher than 1 Bq/g?

Similarly, the various uses of thorium in products such as thoriated welding electrodes or in tungsten electrodes of high-intensity discharge lamps fall under the IAEA definition of consumer products, but would the addition of monazite in jewelry or fabrics be considered as a "deliberate incorporation"?

One should note that this discussion does not only apply to NOR in a narrow sense. Cs-137 that occurs in the environment due to former nuclear weapon tests or nuclear accidents like Chernobyl accident, may result in exceeding exemption values in ashes of timber wood or biomass combustion. Obviously, Cs-137 has not been "deliberately added" to the wood, but what about the "deliberate" use of such wood as raw material for biomass combustion?

The answer to these questions is a regulatory decision, but what matters for a radiation protection practitioner is a correct characterization of the radionuclides present in the product and a sound assessment of the dose impact associated with their use. This is, in any case, a prerequisite for an informed decision on the potential trade and use of these products.

Quite different cases are static elimination devices with a reactor produced "NOR" Po-210 used in industry. These devices can contain several GBq Po-210 and are sold to licensed customers only. Smaller sources with Po-210 below the exemption activity limit of 10 kBq may be used to check or calibrate instruments.

10.4 Which commodities containing NOR are used in industry?

Products containing NOR are not always considered as NORM themselves according to the regulatory definition. In any case, they are manufactured by industries dealing – obviously - with NORM as raw material. Then they are traded and sold to other industries, which often may not be classified as an industry dealing with NORM. Therefore, the industries dealing with NORM-containing products may not be aware of the NOR content of the products they use if the information on the NOR content is not transferred properly.

Products that are not considered NORM according to the regulatory definition still may contain an enhanced activity concentration in NOR compared to the local background. They can trigger an alarm on a radiation portal monitor and consequently hinder the free movement of the commodity; the shipment may be blocked at the border during transportation, which creates an additional administrative burden to explain the alarm. Therefore, it is necessary to have a global view not only on products containing NORM but in general on products that may contain an enhanced activity concentration in NOR.

Typical products containing NOR used in the industry are the following:

- Refractory ceramics and bricks (in particular zirconia-containing refractories)
- Abrasives (composed of corundum or zirconia)
- Building materials
- Fertilisers
- Potassium compound (see Section 10.11)
- Products containing thorium, such as thoriated welding electrodes, thoriated lamps e.g. in the automotive industry, magnesium-thorium or nickel-thorium alloys used in aerospace industry, …

Table 10-1 provides indications on the characterization of these products. Regarding zirconia-based products or phosphate fertilizers, a detailed overview including indications on the dose-assessment may be found in the corresponding IAEA Safety Reports [5,6].

Since radiation exposure and safety management related to the use of industrial used products have already been discussed in detail in previous chapters, this chapter does not cover these topics. A special case comes from potassium salts, a typical product used in the chemical industry (see Chapter 3 and Section 10.11).

TABLE 10-1: PRODUCTS THAT CONTAIN NOR

Products	Dominant radionuclide	Range of activity concentration	Used for
Abrasives (based on zircon or zirconia)	U-238, Ra-226	A few Bq/g	Surface treatments
Abrasives (based on corundum/aluminium oxide)	U-238, Ra-226	0.2 – 0.5	Surface treatments
Ceramic tiles	U-238, Ra-226, Th-232	Less than 1 Bq/g	Building materials
Glass fibers containing zirconia	U-238, Ra-226	~ 1 Bq/g	Building material [7] Chemical processing
Fertiliser	U-238; K-40	Depend on type of fertiliser – see [6]	Agriculture
Potassium salts and mixtures with potassium salts	K-40		Chemical industry, food and feed production
Refractories (based on alumino-silicate)	U-238, Ra-226	0.2 – 0.5	Facilities for high temperature processes (melting, sintering, incineration, …)
Refractories (based on zircon or zirconia)	U-238, Ra-226	A few Bq/g	
Thoriated welding rods	Th-232 + decay products	50 – 150 (between 0.4 and 4% ThO_2 in mass)	Welding in mechanical engineering
Thorium alloys	Th-232 + decay products	10 - 200	Car lamps, aeronautics engines
Thorium chemicals	Th-232 + decay products	Up to 3,800	Used in laboratories or pharmacies.
Uranium chemicals	U-238	Up to 10,000	

10.5 Which consumer products and commodities with NORM are / were manufactured for selling to private users?

The incorporation of natural radionuclides in products used by the general public is an old practice.

- Uranium oxide was used as a pigment in the manufacture of glasses and ceramics for centuries.
- Radium was used for its radioactive properties in luminescent paints in watches and various measuring instruments.
- Thorium was used in the manufacture of gas lantern mantles and also in some camera optics. It is still used for infrared optics.

When these examples correspond to the intentional addition of natural radionuclides in consumer goods, other objects intended for private use may contain an elevated level of natural radiation due to their mineral composition.

- Sanitary ware incorporating zircon or zirconia.
- Building material such as granite counter-top or tiles

- Animal litter
- Jewelry

Several reports [8,9,10] provide an overview of consumer products and consumer goods, including an assessment of their radiological impacts and regulatory considerations.

Many examples and pictures may be found on the website of the „*Museum of Radiation and Radioactivity*“ of Oak Ridge Associated Universities: https://www.orau.org/health-physics-museum/collection/consumer/index.html

In Australia, ARPANSA dedicates some pages on its website on information on consumer products: https://www.arpansa.gov.au/understanding-radiation/radiation-sources/more-radiation-sources/ionising-radiation-and-health/frequently-asked-questions

In recent years, many instances of products involving the mineral tourmaline were detected through random controls at borders. It included:

– Pendant medallions made of tourmaline – with a dose-rate up to 50 µSv/h

– Fabrics and clothes impregnated with tourmaline

– Combs and hairbrushes

– Mattresses containing ceramics

– Washing balls (ceramics-based substitute for washing powder)

Although tourmaline is a non-radioactive mineral, it may contain inclusions of monazite with a significant activity concentration of thorium. The activity concentration is highly variable depending on the origin of the tourmaline. Two case-studies on tourmaline products are detailed in Section 10.8.

10.6 Legacies

Many products containing NORM from the past may still be encountered in museums or private collections. Typically, old watches with radium paint, World War II military items or geological samples. Many of them are easy to find through the usual e-commerce websites.

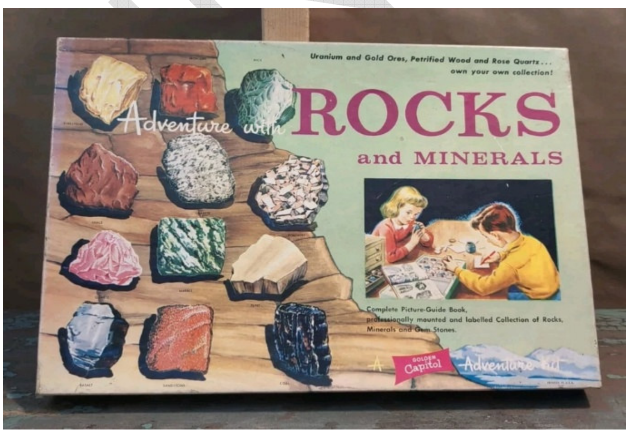

Figure 10-2: This geology kit for kids of the 1950s proudly advertise the presence of uranium and gold ores in its content. It is available for sale on the internet.

Approach to these NORM legacies is generally made on a case-by-case basis. For private use, recommendations on good practice may ensure a sufficient level of radiation protection. For large collections (e.g., mineral samples), an authorization may be required. This is, for instance, the case for the geological collection of the Royal Museum of Central Africa in Belgium, where a significant amount of uranium ores from Congo is stored and requires radon monitoring in the storage space.

10.7 Specific cases of commodities: building material, foodstuff and drinking water

Building materials

We already mentioned building materials as one of the most common commodities containing NORM. Zirconium oxide, for instance, is used in the manufacture of some glazed tiles or sanitary ware [5].

Often, a reference level of 1 mSv/year is recommended to protect against the external exposure due to building material. Screening index, such as the activity concentration index have been derived to allow a quick screening of the compliance of the building material with this reference level. The use of the screening index however is only the first step of a dose-assessment process for which various methods have been proposed.

The issue of NORM in building materials however is already extensively described in other publications [11,12,13,14] and we will not discuss it further.

Foodstuff

Some foodstuff may naturally contain a slightly higher concentration in natural radionuclides. Brazilian nuts for instance regularly trigger the alarm of portal monitors. The activity concentration in Ra-226/Ra-228 varies between 12 and 230 Bq/kg [15], but it does not induce any significant radiological impact[17] on the consumer.

Foodstuff grown in contaminated area may accumulate natural radionuclides. For instance, sea food is known to accumulate polonium [16]. The concentration of natural radionuclides in crops and other food grown in NORM contaminated area is generally subject to appropriate monitoring and is part of the dose-assessment of the contamination: how to monitor and assess contamination of the food chain in contaminated area is the subject of an extensive literature [e.g. 17,18,19,20] and outside the scope of this handbook.

Moreover the manufacturing of feed phosphate and of fertilizer from phosphate ore may raise concern with respect to the consequent bioaccumulation of natural radionuclides in crops or in animals fed with these products. Studies however don't show concerning impacts [6].

Drinking Water

The activity concentration of natural radionuclides in groundwater is highly variable depending on the local geology. Concentration of uranium and activity concentration in radium may sometimes be quite high and raise concern from a radiation protection point of view. Here, we

[17] https://www.bfs.de/EN/topics/ion/environment/foodstuffs/brazil-nuts/brazil-nuts_node.html
https://www.orau.org/health-physics-museum/collection/consumer/food/brazil-nuts.html

also refer to the extensive literature on the subject. WHO has derived recommendations [21] for radionuclides in drinking water derived from a reference level of 0.1 mSv/year to an adult[18].

Like for foodstuff, water supplies potentially affected by a NORM contaminated area should be the subject of appropriate monitoring and, if necessary, of restrictions or remediation.

Water is also one of the most common raw materials used in the manufacturing of products, and the drinking water standards may sometimes be applied to water used in the food industry. Some additives, such as phosphoric acid, which may contain some uranium from the processing of phosphate ore, are also used in the manufacture of soft drinks.

10.8 Regulatory approaches

For products or consumer goods which are considered as NORM and for which the ionizing character of the NOR is not used, the implementation of IAEA requirements into national RP regulations depends on national circumstances and may vary from one country to another.

In all cases, both workers radiation protection and public radiation protection need to be taken into account, either based on reference levels if the exposure situation is considered as an existing exposure situation or based on exemption criteria and dose limits if the exposure situation is considered as a planned exposure situation. The typical use of the product that strongly determines the actual dose must be considered and the decision-making process regarding the appropriate radiation protection strategy for these products requires expert judgment from the decision-maker. Two very different examples are described in the next section.

10.9 Case studies

10.9.1 Regulatory process for consumer goods containing tourmaline in Belgium

According to Belgian Radiation Protection Regulations, consumer goods with an activity concentration above the national exemption level are considered NORM and subject to the regulations applicable to NORM if the natural radionuclides have not been intentionally added to the product.

In practice, this means that the producer (when located in Belgium) or the importer of the product must notify FANC, the Belgian radiation protection regulator. The notification must contain the necessary information to perform a dose-assessment.

Several cases of import into Belgium of consumer products with an enhanced activity concentration involved the use of tourmaline in the product. Tourmaline is a non-radioactive mineral but, depending on its origin, may contain inclusions of monazite with a significant activity concentration of thorium.

[18] The WHO recommendation for uranium however is rather based on its chemical toxicity.

There have been many cases of the use of tourmaline in consumer goods: washing balls, handbags, textiles, etc. We focus here on two cases which went through the regulatory process in Belgium: tourmaline in hairbrushes and in leggings.

Hairbrushes: A shipment of various hairbrushes and combs triggered the portal monitors of the customs in the harbor of Antwerp (Belgium). Customs notified FANC which then took contact with the importer. A radiation protection expert analyzed the material: it showed an activity concentration of 1 Bq/g in uranium-238sec and 5 Bq/g in thorium-232sec for the combs and 6.5 Bq/g thorium-232sec for the hairbrushes. According to the information provided by the importer, the content of the tourmaline in the product was around 3%. The tourmaline was of Chinese origin.

Because tourmaline has piezo-electric properties, the addition of tourmaline to the hairbrushes and combs gave them an anti-static character. In that case, FANC considered that it was an acceptable justification for the addition of NORM into a consumer good. Regarding dose-assessment, the use of these hairbrushes had only a trivial dose-impact considering that only external dose was a relevant exposure pathway and that the external dose in contact with a single piece didn't exceed two or three times the local background.

Consequently, the import and commercialization of these hairbrushes and combs was authorized by FANC. However, it was suggested to the importer to use another source of tourmaline, less rich in monazite inclusions.

In another case, it was a shipment of women leggings containing tourmaline which triggered the alarm of a portal monitor. After contact with the Belgian importer and analysis, it appeared that these leggings contained an activity concentration in Th-232sec of 4 Bq/g. In that case, there was no proper justification to the use of tourmaline in the manufacture of the leggings (it was mainly a commercial argument based on a so-called "positive energy" of tourmaline). The external dose to a possible user was significantly higher as in the case of the hair-brushes and the use of such leggings by pregnant women could not be excluded too. Consequently, FANC prohibited the sale of this shipment of leggings, which was destroyed by incineration.

FANC asked the importer of the leggings to monitor the activity concentration in future shipments. The importer turned then to another source of tourmaline with negligible activity concentration.

10.9.2 Radon Mattress Incident in Korea

1 Background

The "radon mattress incident" was a major issue related to NORM in South Korea, arising in 2018. The trigger of the incident was a TV news report about a mattress which emitted radon. Radon is a well-known carcinogen according to the World Health Organization (WHO). Exposure to radon has been discussed many times, but the incident here was much more severe because the source was a bed, and those most exposed included infants and children. Moreover, the radon concentration levels were reported to be as high as 2,000 Bq/m^3, ten times greater than the recommended limit of indoor radon, 200 Bq/m^3. After the survey and analysis, it was found that the 'radon' in the report was not in fact radon (Rn-222) but thoron (Rn-220). However, the incident grew rapidly because there was no specific guideline pertaining to thoron exposure, especially from bed clothing in Korea and in other countries.

2 Overlooking Thoron (Rn-220)

Thoron was not considered as a source affected by radiation protection laws due to its short half-life. Compared to radon and its by-products, thoron and its by-products decrease rapidly. The activity of thoron was halved after one minute, and less than 0.1% existed after ten minutes compared to the initial amount. The activity of Pb-212, the main contributor to thoron exposure, increased, but the maximum value was 0.14% of the initial activity of thoron. Therefore, there were no countries that regulated thoron, especially from products. Only the IAEA mentioned that if necessary, thoron management could be applied using the method used for radon [22]. However, it was revealed that the thoron could exist as a thin layer on the surface of a product, and if users used such a product with little movement (e.g., sleeping), they may be exposed to thoron radiation.

3 Unjustified 'Negative Air Ion' Marketing

The reason why bed clothing emitted thoron was related to the use of monazite. Monazite was both a rare-earth element (REE) ore and a thorium ore, containing 4~9 weight percent of thorium. The chemical formula of monazite was (Ce, La, Y, Th)PO_4, and the density was 4.6-5.4 g/m^3. Some countries use thorium as a fuel at nuclear power plants, and monazite was classified as both a NORM and a nuclear fuel material in Korea.

Manufacturers included monazite in their mattresses to create negative air ions. Negative air ions are commonly known to be beneficial to human health, though without any specific evidence, in East Asia. According to a study by Alexander et al., there is no direct evidence that negative air ion benefits health according to the results of studies over 60 years [#&]. However, many people believe that negative air ions are good for health; therefore, numerous types of products have been produced.

4 Impacts

By December 2018, the scale of the incident had become massive. More than 70,000 mattresses, from 29 brands, were recalled according to the Act. The maximum radiation exposure for a mattress user was reported to be 13.7 mSv/y. The main contributor to this level of exposure was thoron inhalation, and the radiation exposure by other pathways (external and dust inhalation) could be neglected. The manufacturer closed their business and has since struggled with court battles.

However, the problem with products containing negative air ions is ongoing. Other brands of mattresses and other type of products, not only bed clothing (e.g., latex mattresses, pillows, blankets) but other types of products (e.g., accessories, beauty products, clothes) have been revealed. For example, for blankets, it was reported that the user may be exposed to 64.1 mSv/y of radiation. The investigation and analysis continue.

5 Regulatory Paradigm Shift in Korea

To overcome the radon mattress incident, the Korean Nuclear Safety and Security Commission (NSSC) announced the enforcement of NORM regulation, especially as it pertains to NORM-containing products. According to the announcement, all types of NORMs exceeding registration levels shall be registered, including the manufacturers that manufacture the NORM products. Moreover, only registered NORM handlers can distribute and use NORMs. In addition, the use of NORM in consumer products intended for close contact with the human body is strictly prohibited. Also, it is illegal to advertise the effectiveness of NORM products, such as advertising beneficial health effects of products including negative air ions. Through these regulatory updates, Korea has established a strict management framework to prevent unjustified public exposure to thoron from consumer products.

10.10 Trade of goods containing NORM

One of the challenges in the trade of goods containing NORM is the correct transfer of information from the producer of the goods to the end-user, including the intermediary steps. Even if most goods containing NORM should not be transported as class 7 radioactive material (see Chapter 8), they will frequently trigger alarms on radiation portal monitor at borders, what can lead to additional administrative burden and in some cases to denial of shipment[19].

Alarms on portal monitors due to NORM shipments are extremely frequent: for instance, in the harbor of Antwerp (Belgium) around 15 000 containers come through every day; the alarm rate on the portal monitors of the harbor is 1,45%, which corresponds to 224 detections per day [24]. Such a large number of detections requires a well-defined screening procedure where "innocent" NORM detections (such as shipment of ordinary granite tiles) needs to be discriminated from abnormal NORM detections (such as enhanced NORM activity concentration in unusual consumer goods – such as handbags or hairbrushes, see case-studies in section Regulatory process for consumer goods containing tourmaline in Belgium10.9.1) or smuggling of radioactive sources of nuclear materials (the basic motivation behind portal monitor detection).

Protocols are developed by customs to support this identification: it combines measurement results (alarm level on the portal monitor, dose-rate and nuclide identification) and expert judgment on the nature of the shipment supported by a pre-established list of "innocent" NORM materials. IAEA developed an app to help this identification: the TRACE app[20] (Tool for Radiation Alarm and Commodity Evaluation) provides information on a list of ~ 120 commodities types which usually cause alarm on portal monitors due to their natural radionuclides content.

To effectively monitor trade involving NORM, a clear classification system is also required. The most practical criterion for this purpose is the Harmonized System (HS) Code provided by the World Trade Organization. The HS Code categorizes all internationally traded goods into 97 sections and further subdivides them into a structured classification system. While originally developed to harmonize tariff imposition and trade regulations among nations, its broad applicability and systematic structure make it a valuable tool for monitoring and managing the trade of NORM-containing goods.

Ideally radioactivity should be mentioned in Material Safety Data Sheets (MSDS) when exemption values are exceeded (K-40 is a "special case"; see below). That would allow users of such products to be informed about the radioactive content of the products. They could then refer to the corresponding national regulations, and assess the potential risk associated with the use of the product.

In practice, it is not yet often the case however. But still, MSDS or any other documents about the composition of the product may provide useful information to guide the characterization.

[19] Denial of shipment affects even more NORM goods which are transported as class 7 material. See IAEA working group on the subject: https://gnssn.iaea.org/main/fastram/Pages/What-Delay-Denial-Shipment.aspx

[20] https://www.iaea.org/newscenter/news/iaea-launches-mobile-application-tool-for-radiation-alarm-and-commodity-evaluation

The indication on chemical composition given in the MSDS, even if it doesn't mention explicitly radioactivity, will support the expert judgement on the NORM content. E.g. if the composition of refractories includes zirconia, it is likely that the activity concentration will exceed 1 Bq/g; on the other hand, if the composition is based on aluminum oxide (or its other names such as corundum, alumina, …), then it is unlikely that the activity concentration will exceed 1 Bq/g.

For some products, the radioactivity content is explicitly mentioned. Thorium welding electrodes for instance have a specific code T04, T10,… T40 which refers to the percentage of thorium oxide in the electrode: T04 means 0.4% thorium oxide, T10 = 1% thorium oxide, etc.

10.11 Special case: Potassium-40

10.11.1 Introduction

1 gram of potassium contains around 30 Bq of its radioactive isotope K-40. Therefore, all potassium-based products contain an activity concentration in potassium-40 which may exceed the IAEA exemption level of 10 Bq/g. However, as explained in Chapter 2, due to the homeostasis of potassium in the human body, the radiotoxicity of K-40 is very low, and external exposure is the only relevant exposure pathway related to K-40. This is why most products with a K-40 activity concentration above 10 Bq/g are not of concern from a radiation protection point of view, except in very specific exposure circumstances. Therefore, some countries such as the Netherlands, have implemented in their regulations specific exemption criteria for K-40 [25].

In Chapter 3, the industrial use of potassium salts with activity concentration above 10 Bq/g is summarized. The industries that use these salts are typically not considered NORM involving industries. However, K-40 activity concentration may be a constraint in the context of the use or recycling of products or residues into building materials. For instance, the K-40 activity concentration in fly-ashes from biomass combustion may reach a few Bq/g, and consequently, the activity concentration index of the product may be higher than 1.

This section gives a list of the most common potassium-based products. It shows through a case-study how the absence of specific exemption criteria can create unnecessary regulatory burden.

10.11.2 Fertilizers

To improve agricultural yields productivity, soils can be enriched with potassium through the use of potassium fertilizers. Potassium fertilizers contain e.g. industrially produced potassium chloride (KCl). Pure KCl contains 52% potassium. The activity concentration of pure KCl, deduced from the activity concentration of pure (metallic) potassium, is therefore around 16 Bq/g (note that KCl is virtually never more than 95% pure).

10.11.3 Salts in industry

In industry, potassium salts can be used for surface treatment, electroplating, soldering salts, additive to foundry products, etc. An overview of these applications is given in Chapter 3. However, potassium salts are also largely used in the food industry. Table 10-3 gives a list of potassium-based feed additives permitted in the European Union with an activity concentration above 10 Bq/g.

TABLE 10-2: IN THE EU PERMITTED FOOD OR FEED ADDITIVES WITH POTASSIUM EXCEEDING 10 BQ/G K-40

Chemical name	E-No.	K-40 [Bq/g]
Potassium metabisulfite	E224	11,0
Potassium hydrogensulfite	E228	10,2
Potassium nitrite	E249	14,3
Saltpeter, Potassium nitrate	E252	12,1
Potassium acetate	E261	12,4
Potassium propionate	E283	10,9
Tripotassium citrate	E332	11,3
Potassium tartrate	E336	10,8
Dipotassium phosphate	E340	14,0
Tripotassium phosphate	E340	17,2
Potassium malate	E351	11,6
Potassium adipate	E357	11,0
Potash	E501	17,7
Potassium hydrogencarbonate	E501	12,2
Potassium chlorid	E508	16,4
Potassium sulphate	E515	14,0
Potassium hydroxide	E525	21,7
Potassium ferrocyanide	E536	13,2

10.11.4 Case example: Powdered milk

In France, a "premix KCl", dehydrated, used to produce milk for babies, was out of date. So, it had to be disposed of as waste. When the truck entered the landfill, the radioactivity detector was triggered. After sampling and measurements, it appeared that the mass concentration was 13 Bq/g, slightly lower than pure KCl but exceeding the 10 Bq/g exemption value, leading in French regulation to its prohibition of use in foodstuffs in spite of the negligible radiological impact.

This shows the importance of implementing specific exemption criteria and procedure in regulations.

10.12 Literature Chapter 10

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11 Views and Experiences of Different Regions

11.1 Insights of Radiation Protection in Industries involving NORM in African Countries

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11.1.1 General information

Africa is a vast continent with a wide range of resource development activities associated with Naturally Occurring Radioactive Material (NORM). While NORM is ubiquitous in nature, some human activities can result in the production of NORM with enhanced radioactivity levels. Besides uranium production, activities known to leave a NORM footprint include oil and gas extraction, phosphate production, burning of coal, water treatment, and mining of mineral sands, precious metals, and non-uranium metal ores. It is important to note that for most human activities involving low-radioactivity mineral ores, radiation exposure is not significantly greater than normal background levels. However, when ores are introduced into an industrial process, radionuclides can become more concentrated in by-products or waste material. A good example is red-mud, a by-product of bauxite mining. Such activities may therefore require regulation to ensure radiation protection of people and the environment.

Mining activities are increasing in Africa, and with this, some countries have instituted projects to better organize the sector for socio-economic sustainability and development. The Government of Cameroon, for instance, instituted a national project to strengthen the mining sector's capacities. The project, which ran from 2012 to 2017, resulted in the discovery of substantial mineral resources, including uranium, thorium, gold, diamonds, bauxite, copper, rutile, cobalt, iron, and rare-earth metals. Further exploration, however, is required to confirm their economic worth. Like most African countries, Cameroon's mineral resources are largely unexploited, as currently only gold is mined. In Ghana, over a third of the country's revenue results from mining activities with gold, diamond, bauxite, and manganese mined on a large scale [166] [167]. In Kenya, titanium ore and zircon were mined until December 2024, when mining concluded due to depleted ore reserves [168]. Although yet to be mined, Kenya has high-grade niobium deposits [169] in addition to potential uranium deposits [170]. Morocco is known for the production of phosphates and building materials, while in Malawi, uranium mining is set to resume in June 2025 after being under care and maintenance since 2014. Current active mineral mining in Malawi involves phosphate, coal, limestone, and iron, while rare earths, such as rutile and graphite, discovered in 2019, are considered the world's largest natural deposits for rutile and among the world's largest for graphite, are yet to be exploited. Oil and gas in Malawi remain in the exploration phase.

It is crucial to point out that nearly all mineral resources from Africa are not used in the countries of origin. Key destinations for these minerals include China, the European Union, and the United States. France, for instance, is heavily reliant on uranium from Niger, one of the world's largest uranium producers [171]. Despite its uranium-fuel production capabilities, Niger does not have a nuclear power plant. South Africa is the only country in Africa with a commercial nuclear power plant, supplying about 5% of the country's electricity. Moreover, although more than half of African countries have critical minerals necessary for the global shift towards clean energy, none have fully harnessed these vital resources.

Table 11-1 outlines strategic minerals and key producers as of 2005.

TABLE 11-1: STRATEGIC MINERALS AND KEY PRODUCERS [172]

Material	Percent of world production	Countries contributing to the percent of world production
Diamonds	73%	Botswana 35%; Congo (Kinshasa) 34%; South Africa 17%; Angola, 8%
Gold	89%	South Africa 56%; Ghana, 13%; Tanzania, 10%; and Mali, 8%
Uranium	16%	Namibia 46%; Niger 44%; South Africa less than 10%
Bauxite (for aluminum)	9%	Guinea 95%; Ghana 5%
Steel	2%	South Africa 54%; Egypt 32%; Libya 7%; Algeria 6%
Aluminum	5%	South Africa 48%; Mozambique 32%; Egypt 14%
Copper (mine/refined)	5%	Zambia 65%/77%; South Africa 15%/19%; Congo (Kinshasa) 13%/0%; Egypt 0%/3%
Platinum/Palladium	92%	South Africa 97%/96%
Coal	5%	South Africa 99%

Studies indicate that industries processing natural resources and raw materials associated with NORM may result in technologically enhanced levels of naturally occurring radioactive materials (TENORM), which may require regulation and radiation protection. These activities have been carried out for several years, with or without the required radiation protection infrastructure to mitigate radiological hazards, probably because, for most countries, radiation protection is mainly focused on sealed sources used in mining and industry, as well as medical applications such as X-rays and radioisotopes like I-131.

The growing global demand for mineral resources is driving mining expansion across Africa. While this supports socio-economic development, it also raises concerns, such as the management of NORM residues with elevated radionuclide levels and the control of illegal and artisanal mining activities that can deprive governments of revenue, create social tensions, and exploit vulnerable communities. To ensure sustainable progress in Africa's mining sector, it is important to balance economic growth with sound practices.

11.1.2 Survey

To gain insights on how African countries handle NORM and mining concerns, researchers from Cameroon, Ghana, Kenya, Malawi, Morocco, Germany and Australia through their involvement in the IRPA task group on NORM, developed a digital questionnaire which they used for their research. The questionnaire, which was largely based on a previous European survey conducted by the IRPA TG on NORM waste disposal, considered the following thematic areas:

NORM knowledge and NORM research

Risk and regulation

Key challenges

The overall objective of the research was to identify gaps in the mining sector and recommend actionable measures for safe and sustainable mining operations.

The questionnaire was shared with research institutions, regulatory authorities, universities, radiation specialists, and technical service organizations and experts across nineteen African countries, as shown in Figure 11-1.

FIGURE 11-1: COUNTRIES FROM WHERE RESPONSES WERE OBTAINED

11.1.3 Results and Discussion

a. NORM knowledge and NORM research

Although most respondents associated NORM with industries, homes, and mines, they defined NORM as a material that contains radioactive elements, regardless of concentration, citing soil and water as examples. Nearly all respondents reported the presence of NORM-producing activities in their countries, with ownership ranging from government, private, foreigners, and non-legal artisans. The respondents acknowledged that NORM industries posed radiological risks to the public, workers, and the general environment and should therefore be regulated, but were unaware of any special procedures enforced before NORM waste was disposed of, such as testing before disposal. It was also observed that the public is largely unaware of NORM-related risk.

From the responses, it is apparent that most respondents do not fully comprehend what NORM entails from regulatory and radiological protection perspectives. In a regulatory context, NORM refers to materials that are likely to contain significant concentrations of radionuclides, such as sludge and tailings generated by the extraction process. The answers provided seemed more like textbook answers. This, nonetheless, is not surprising because according to the survey, most research on NORM is carried out by postgraduate students and for academic reasons only, and may therefore be prone to copy-pasting without necessarily understanding the information. In Morocco, for example, the respondents, mainly drawn from the university, appeared to know about Radon, Uranium-238, Thorium-232, and Potassium-40, but could not relate this to NORM and TENORM in industrial settings. In general, the uptake of the student's research by the regulator was found to be poor.

b. Risk and Regulation

Most respondents were not aware of any NORM regulation in their countries but were aware of the existence of regulatory bodies with the required independence, financial support, and the ability to enforce an effective licensing, inspection, and management of radioactive material and NORM where applicable. In Kenya, for example, the Kenya Nuclear Regulatory Authority (KNRA) has this mandate, while the Atomic Energy Regulatory Authority (AERA) is responsible for all radionuclide and radiation regulation in Malawi. In Morocco, the AMMSSNuR agency has the mandate. While most African countries don't have active NORM legislation and regulation in place, plans are underway to set these up. In Kenya, radiation protection regulations are at the draft stage, with NORM covered under the planned exposure situations section and in line with the IAEA basic safety standards (BSS). In the survey response, the Malawi regulator indicated that they had developed specific NORM regulations that were, at the time of administering the survey, currently being vetted by the country's Ministry of Justice. Other countries that stipulated drafting of NORM regulation legislation include Zambia and Ethiopia, while countries that confirmed the existence of NORM legislation include Nigeria, Egypt, and South Africa. Only a small fraction of the respondents was aware of the graded approach and the BSS although the majority did not appear to understand their meaning apart from the researchers via their published research papers related to the assessment of natural radioactivity. Without an active legislation and regulatory framework in place, it is nearly impossible for most African countries to enforce NORM risk management strategies.

c. Key Challenges

The responses identified the following comparable challenges in all the African countries in their approach and practices for NORM management.

Insufficient NORM knowledge and research: Most countries don't quite understand what NORM is, hence fail to see the need for management of and radiation protection in NORM-producing industries and activities. Research and data on NORM is also limited due to insufficient funding, limited NORM equipment and oftentimes lack calibration materials leading to grounding of equipment. Additionally, the absence of modern training facilities and simulation tools hampers the ability to train personnel in the latest NORM measurements and management practices. These challenges may be addressed by conducting training exercises for NORM workers as well as the management to sensitize them on the importance of radiation protection and regulation in the NORM industry. Research output and uptake can be enhanced by forging partnerships between research institutions and universities on one hand and regulatory agencies, industries and international collaborators on the other.

Lack of Radiation Safety Culture: Generally, radiation safety culture in NORM industries among many African countries is absent. This is occasioned mainly by an inadequate understanding of NORM and potential risks therein, probably because most institutions of higher learning in Africa do not have modules or courses specific to NORM, with radiation protection space mainly allocated to programs such as medical physics, nuclear physics, or nuclear safety and security. One way to resolve this is to introduce the principle of radiation safety to potential workers, for example, university and college students, while they are still in school, by embedding radiation safety into the school curriculum, for example, relating NORM activities, such as uranium production, to existing programs such as nuclear safety and security. This is in addition to teaching about the different sources of radiation exposure, the risks and benefits of radiation exposure, and emphasizing the importance of safety protocols and responsible behavior in situations that may lead to increased radiation exposure. In-service training of workers can also be used to target specific radiation protection needs in the NORM industry.

Inadequate Training and Certification: For most African countries, radiation exposure is associated with closed sources, and hardly in exposure situations involving NORM. This is compounded by the absence of formal education and training programs in NORM protection and regulation. These inadequacies give rise to the shortage of qualified radiation protection experts specializing in NORM. Incorporating courses in higher education that are specific to NORM, or partnering with national, regional, and international bodies to offer short-term training courses in NORM management, may help ease these challenges. On top of that, introduction of national and regional professional NORM associations can also help reinforce the importance of relevant training in the NORM field.

Inadequate Regulation for Working Procedures: Many African countries don't have legislation in place to regulate the NORM industry. Kenya for example is at the draft stage and with no legally binding document in place, it is nearly impossible to enforce radiation-related compliance. For North African countries in general but particularly in Morocco, formulation of regulation on management of NORM waste (for instance the production of phosphogypsum) and the transport of NORM material are progressing following the creation of the Moroccan agency of nuclear security and Radiation Safety.

11.1.4 Conclusions

Africa's role in ensuring the protection of workers, the public, and the environment against radiation exposure due to NORM-related industries underscores Africa's commitment to the safe management of NORM waste and residues. NORM knowledge and NORM research in most African countries, however, are limited. Besides, most countries lack NORM regulations for industries involving NORM regarding radiological impacts on people and the environment. African countries are also dogged by challenges related to infrastructure and capacity for NORM management, for instance, inadequate qualified personnel, a NORM database, well-equipped NORM labs, and NORM legislation. With an increase in NORM-producing activities, most African countries have begun the process of addressing some of these challenges.

11.2 Asia Oceania

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11.2.1 General information

Of all the regions in the world, the "Asia Oceanic" (AO) is by far the most diverse. The exact definition of the region is not precise, and other names such as Asia Pacific are commonly used. However, generally it includes the oil-producing countries of the Middle East, India and Pakistan in the west to Mongolia and China in the North[21], Japan in the northeast, Australia and New Zealand in the south, and many of the Pacific Islands in the East. All countries in between, such as Thailand, South Korea, Malaysia, Indonesia, Vietnam, and the Philippines, are also included, as well as many other countries not listed here.

Almost half the world's population lives in this large geographical region, and it is characterized by the diversity of cultures, political systems, and lifestyles. The health and economic status of different countries also vary significantly.

Medical uses of radiation are growing throughout the region, with assistance and cooperation programs, and a number of countries are using nuclear power generation, with many more looking to install capacity.

From a NORM perspective, the region is unique because it is a major supplier of raw resources and processor of raw materials, which produces refined products for the world economy (see Table 11-2). This also results in very high levels of transport and trade, with the region featuring several transport hubs, such as Singapore and Hong Kong.

Two of the largest economies are China and India, who play important roles. Both countries have numerous raw material deposits and operate extensive mining industries. However, they also have strong industrial sectors.

TABLE 11-2: AO SHARES OF WORLD PRODUCTION IN NORM-RELATED MINING AND INDUSTRIAL SECTORS

[21] Large parts of Russia are also part of Asia, but culturally and historically, this part of Asia has a European character.

Sector	AO Share of world production	Main Producers in AO	Comment
REE Mining	84 %	China, Myanmar	[173], 2024
Iron Ore Mining	62%	Australia, China, India	[173], 2024
Crude Steel	76%	China, India, Japan	[174], 2025
Coal	Ca. 80%	China, India, Indonesia	[173], 2024
Crude Oil	43%	Saudi Arabia	With Russia 54 % [173]
Phosphate	54 %		[175] 2023
Bauxite Mining	57%	Australia, China, Indonesia	[173], 2024
Aluminia	80%	China, Australia, India	[173], 2024
Aluminum	75%	China, India	[173], 2024
Copper Mining	20%	China, Indonesia, Australia	[173], 2024

Another region with specific properties is Australia. Australia is a highly developed economy with a strong mining sector. Similar to the states in North America, Australia is a federal state with multi-level regulatory systems.

As individual countries in the region develop their national sovereign capability, there is likely to be a shift in the trade of various materials.

It is important to note that there is no single approach to NORM in the region and countries are at various levels of development. Many regulatory systems for NORM have evolved from nuclear power regulation systems, as is the case for China and India.

Despite this, there are common challenges in the region.

11.2.2 Approach to Radiation Protection

The majority of countries in the region are signatories to the IAEA and therefore subscribe the standards and guidelines of the IAEA. Each country has its own radiation protection laws, which adopt the IAEA standards.

Countries of the region have developed a robust legal and institutional framework that incorporates safety codes, standards, and guidelines for managing radioactive materials, particularly those from non-nuclear industries.

In all cases, the regulatory framework aligns with the International Atomic Energy Agency (IAEA) standards, particularly the Basic Safety Standards (GSR Part 3 [5]). However, due to a range of circumstances, including national priorities and local socio-economic conditions, differing versions of IAEA documents and varying interpretations of their requirements result in inconsistencies across the region.

The Asia Oceanic Association on Radiation Protection (a regional association under IRPA), is a formal way for radiation protection practitioners to align on radiation protection practices. Most of the larger countries have national radiation protection societies that enable practitioners to interact and develop knowledge and skills. Networks have developed in the region, and a good example is the Asia Oceanic Radon Association, which was modeled on the European Radon Association. There is also regular regional radon measurement intercomparison exercises. These trans boundary initiatives aim to build a stronger knowledge base and establish common practices.

For the region, it can be said that due to the diversity, there is no one set of rules that applies to all countries in the region; however, there is extensive intercountry collaboration and support.

11.2.3 Main NORM aspects

The Impacts of Resources

The region is a major international leader and contributor of resources for the world, and this has significant NORM-related impacts.

Due to varying socio-economics, infrastructure, and capability in the region, many resources are mined and beneficiated in one country and then shipped to other countries for processing. This enables economies of scale, allowing larger, more cost-effective processing facilities (such as smelters and blast furnaces) to process raw materials more efficiently. Many of these facilities exist in China and India. Also, many raw materials are shipped to other parts of the world for further processing. Some countries in the region still have sovereign processing capability, enabling them to develop commodities from "mine to market". But in general, the region is an interconnected web of sources of raw resources (mines) and value-adding processing facilities. An example of this is the relationship between Australia and China, where Australia produces almost 1 billion tonnes of iron ore each year to feed steel-making blast furnaces mainly in China. Some of this ore production also feeds facilities in Japan and the Republic of Korea. As is well known, all raw resources contain naturally occurring radionuclides.

This interconnectivity is an important feature of the region and is important when considering NORM and radiation protection aspects. All commodities contain varying quantities of naturally occurring radionuclides.

The movement of raw materials for processing and the fate of radionuclides pose a challenge for the region, as they require ensuring that radiological risk is equitably and adequately addressed at all stages.

For larger commodities such as iron ore and coal, the potential radiological impacts are low, however, particular resources such as rare earth concentrates, mineral sands and some base metal concentrates contain elevated concentrations. In most cases, these raw resources have radionuclide concentrations that exceed 1 Bq/g and are legally defined as "radioactive". In some cases, the activity concentrations can be of the order of 1,000's of Bq/g. While these raw resources are classified as radioactive, in many cases, they do not exceed the "times 10" factor prescribed by the IAEA Transport Regulations – meaning that the regulations do not apply to their transport. (This creates interesting situations where a facility may need to be licensed for handling radioactive materials, the material can be transported without consideration to radiation aspects, but the customer may need to be licensed to process radioactive materials.)

Another important aspect of the interconnectivity is the management of waste streams, which may be classified as radioactive and require significant levels of control.

High Background Radiation Areas

Within the broader region, there are a number of areas in different countries that can be defined as areas with "high background radiation areas (HBRA)". While these areas are not immediately defined as NORM areas, there is an inconsistent approach to how exposures are handled. In many cases, these areas are associated with elevated radon concentrations, and in some cases, the concentrations can be changed and enhanced through human activities such as domestic situations (for example, residences) or occupational situations (such as workers coming into these HBRA's for the purposes of work or enclosures which increase concentrations. The converse is also true in some cases, where workers come from residential areas with higher background radiation to workplaces with lower exposures. These situations are challenging to manage in a coordinated way, and representatives from the region have been providing input to standards being developed by the IAEA.

A primary effort for HBRAs is formal characterization. There is growing inter- and intra-country collaboration occurring, mainly through research institutes, to better understand the size and extent of possible HBRA areas. Developed countries and international organizations (such as the IAEA) provide advice, education, and assistance to developing countries in this regard. The programs also serve as a mechanism for broader competency development.

A challenge in the region (and elsewhere) is the need to improve research on HBRAs. There is a tendency to use HBRAs as a means of attracting additional research support by linking monitored levels with radiation dose risk factors and reporting them as potential additional cancers. Unfortunately, this misrepresents radiological risk, leading to unnecessary fear and concern.

NORM Wastes and Residues

For the region, where regulatory systems and competencies are developing in many countries, there are varied requirements for, and approaches to, NORM residues and waste management. This is a broader issue which generally applies worldwide but tends to be amplified in the Asia Oceanic region, where the shipment of raw resources for offshore treatment is common. In general, processing waste (which may be enhanced in natural radionuclides and other contaminants) is managed in the country of processing, not the country where the raw materials are produced. While this regional dispersed model of mining and subsequent processing is beneficial commercially and socially (for example, by providing employment), ensuring that the radiological risks are equitably managed between supplier and producer is a challenge. Evidence of where this has failed is the presence of legacy waste sites, which require remediation into the future. An important challenge of the region moving forward is ensuring that developing countries, with the least capacity to deal with these situations, do not bear the burden of future environmental risk.

Low-level NORM wastes can be extensive and massive volumes (thousands to millions of tonnes). Of note is the fly and bottom ash wastes from energy production from coal burning. While not all wastes are NORM wastes, large quantities have elevated radionuclide concentrations and therefore require appropriate management and controls. Other waste streams managed in the region include:

- Large volume, low activity mining and processing streams, just as tailings or waste rock
- Higher activity and medium volumes of scales and sludges the oil and gas industry
- Higher level and lower volume contaminated waste streams from rare earth production
- Large volumes of contaminated liquids.

A feature of NORM waste and residues is that it can be both solid and liquid, each of which requires different control and containment methods.

As resources around the world become more constrained, there is a move to reconsider wastes and residues for either further processing or as raw resources. For example, some mine waste material can be used as construction materials. This requires careful and complex consideration of the potential radiological impacts to ensure that the potential resource is not over-regulated or under-regulated.

Identifying NORM Activities

As already noted, the region is characterized by a spectrum of national regulatory and company expertise and capability. This can lead to challenges in identifying activities and practices with NORM, with some activities being uncontrolled and unregulated. A recognized approach used in other jurisdictions around the world is to have a "positives" list, which specifically identifies the industrial activities that need to be assessed; however, this is not the case in many countries in the Asia Oceanic region. While the larger countries tend to have well defined identification processes, this is not generally the case for developing countries. For the developing countries, the larger companies tend to adopt international best practice, and manage risk, although this is not uniform.

This is partly due to the developing nature of many countries in the region, leading to a lack of adequate and appropriate regulation.

Public Awareness (incomplete)

In some countries, there is limited public and worker awareness of NORM, with a tendency to be immediately fearful of any mention of radiation.

Improved STEM education and public awareness is necessary in developing countries.

restricted regulatory competencies for RP in NORM on the federal level.

What role do the recommendations of ICRP and the IAEA standards play?

How is the transnational cooperation in RP?

Capability and Capacity (incomplete)

- Very diverse
- Wide spectrum of capability
- Extensive practical research in the region, which develops capability
- Area supported by international organizations such as IAEA and ICRP

Summary (incomplete)

- Region is highly diverse and at different levels of regulatory development, with some of the largest economies in the world
- The region is characterised as an interconnected web of resource development
- Major supplier of resources to the world economy

11.2.4 Case example: India

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India has its own indigenous nuclear technology and hence strictly adheres to strict regulations and regular monitoring of radioactivity and radiological dose assessments in the nuclear sector. Specifically, the dose records for the occupational workers are available in public domain. However, the non-nuclear sector of India dealing with NORM and Technologically Enhanced NORM - TENORM, remains oblivious regarding the necessity of regular radiological monitoring and risk assessment in their sector. India's rapid industrialization in sectors such as thermal power plants using coal, oil, and gas extraction, fertilizer production, uranium ore mining, and rare earth mineral processing has led to the generation of significant quantities of NORM. Industrial activities often concentrate radionuclides such as U-238, Th-232, and Ra-226 into by-products like coal ash, phosphogypsum, and oilfield scales, resulting in Technologically Enhanced NORM (TENORM). For instance, coal-fired thermal power plants produce millions of tonnes of fly ash annually, which contains elevated levels of radioactive isotopes. Similarly, phosphogypsum waste from fertilizer industries and scales from oil drilling operations pose long-term radiological risks to workers, nearby communities, and ecosystems. Activities such as mining of minerals, chemical processing of ores, coal-fired power plants, petroleum industry, construction industry, phosphate fertilizer plants, etc., are well known to produce TENORM. Even some small-scale industries and products, such as glass and ceramic industries, use uranium compounds in glassware, dentistry, ophthalmic glass, etc. Thorium is used in gas mantles and welding electrodes. Addressing these challenges requires a balance between industrial development and the implementation of robust radiation protection frameworks. Although some past research has focused on radioactivity measurements in products and by-products from major Indian industrial sectors, viz., the coal and fertilizer industries, there is a paucity of data on this, which makes it difficult to assess the radiological impact in the non-nuclear sector.

Regulatory Body

The Atomic Energy Regulatory Board (AERB), India's apex nuclear safety body, oversees radiation protection in NORM industries. India has made significant strides in NORM management, developing a robust legal and institutional framework under AERB, which essentially includes safety codes, standards, and guidelines for managing radioactive materials, particularly those from non-nuclear industries. Technological advancements in NORM management include the recovery of valuable radionuclides from waste for societal applications and ensuring the safe management of radioactive waste, according to the Bhabha Atomic Research Centre (BARC). The regulatory framework aligns with the International Atomic Energy Agency (IAEA) standards, particularly the Basic Safety Standards (GSR Part 3 [5]). Key regulations include the AERB Safety Code SC/MED-4 (2011), which provides guidelines for radiation safety in mining and mineral processing, and mandates Environmental Impact Assessments (EIAs) for industries involving NORM. While large-scale industries adhere to AERB protocols, smaller operations often lack awareness or resources to comply, highlighting the need for grassroots outreach.

AERB ensures compliance by hospitals, universities, and other radiation facilities through a number of activities, including "surprise inspections, review of the periodic safety status reports submitted by the facilities, safety performance appraisals of the facility while renewing its license."

AERB also brought out the regulatory guidelines for industries using NORM, such as beach sand processing, phosphate rock processing etc., some of the documents listed below.

1. AERB Safety guidelines No. AERB/FE-FCFSG-5 (2013). "Radiological Safety in handling beach sand minerals and other Naturally Occurring Radioactive Materials.
2. AERB Safety directive No. CH/AERB/IPSD/78/2009. "Use of Phosphogypsum in Building & Construction Materials & in Agriculture".
3. AERB Safety Guidelines No. AERB/NF/SG/RW-5 (2007). Management of Radioactive Waste from Mining and Milling of Uranium and Thorium.
4. AERB Safety guidelines No. AERB/FE-FCF/SG-2 (2007). Radiological Safety in Uranium Mining and Milling.

Radiation Protection in industries involving NORM

NORM is also encountered in other industrial activities such as processing of Beach Sand Minerals (BSM), processing of Columbite Tantalite Ore, fertilizer industries handling Rock Phosphate and Phosphogypsum, oil and gas industries, as well as in fly ash and tailings from processing of aluminum, zinc, tin, copper etc. Regulatory control in NORM-related industries ensures that all activities, including the handling and management of residues, are carried out safely within the prescribed dose constraints and other safety requirements set by the regulatory body. A graded regulatory approach is particularly relevant to operations involving exposure to NORM. The regulatory control exercised in industries involving NORM in India has significantly contributed to improving the radiological safety and the management of NORM-bearing residues.

Technological advancements play a pivotal role in addressing NORM challenges. IoT-enabled radiation sensors, deployed in thermal power plants, enable real-time monitoring of radiation levels in fly ash, ensuring compliance with safety thresholds. Geopolymerization, developed by BARC scientists, immobilizes radioactive residues by binding them into stable ceramic-like matrices, reducing radionuclide leaching by over 90%. Meanwhile, AI-driven predictive models, piloted by IIT Madras, forecast TENORM accumulation in oil pipelines, allowing preemptive maintenance to minimize worker exposure. These innovations reflect India's shift toward integrating cutting-edge technology with traditional radiation safety practices

Challenges

Despite progress, India faces persistent challenges in NORM management. The reporting of radioactivity in nonnuclear sectors is found to be very poor. Coal and Fertilizer industries have been monitored to some extent but not sufficiently. Radioactivity in construction and tobacco industries also has been only scarcely reported. Other industries were found not to be recognised for risk assessment from radiological point of view at all. Public awareness remains low, with communities often unaware of actual radiological risks associated with NORM waste

IARP

In India, radiation protection is overseen by AERB and the Indian Association for Radiation Protection (IARP). The AERB enforces the Atomic Energy (Radiation Protection) Rules, 2004 to ensure the safe use of ionizing radiation and nuclear energy. IARP, a non-governmental organization, promotes radiation safety, provides a platform for professionals to interact, and organizes conferences and workshops. The list of RSO courses organized by IARP in association with BARC are :a) "Training cum RSO Certification Course on "Radiation Safety Aspects of Container Scanners", b)"Training cum RSO Certification Course on "Radiation Safety Aspects of Nucleonic Gauges" association IARP conducts one annual conference, holds topical meetings and workshops on subjects of current interest related to safety aspects in the applications of ionizing radiations and radioisotopes in various field.

Future Directions and Conclusion

Circular economy initiatives, such as recycling NORM waste into road construction materials (as per BIS Standards, 2023), could reduce environmental burdens. Academic curricula are being revised to include NORM-specific radiation safety modules, while partnerships with industries aim to bridge skill gaps. By prioritizing innovation, education, and global cooperation, India seeks to establish a sustainable framework for NORM management that safeguards both development and public health. India's approach to NORM combines rigorous research, technological innovation, and international collaboration. While challenges like regulatory fragmentation and awareness gaps persist, strategic policy reforms and capacity-building initiatives position the country to lead in sustainable radiation protection practices.

11.3 European experiences

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11.3.1 General information

To understand and categorize radiation protection for NORM in Europe, it is necessary to provide information on the framework conditions under which this radiation protection developed.

Europe, a continent of 10.5 million km², is geographically the western part of Eurasia and politically often associated with the European Union (EU), which comprises 26 states but does not include all European countries. With a long cultural history, many nation-states only reached their current borders in the 20th century. Differences in language, governance, and legal traditions lead to varied approaches to radiation protection, including in NORM-related industries.

Europe played a key role in the history of radioactivity: it is where radioactivity was discovered and where the ICRP was founded in 1928 in Stockholm. Although modern radiation protection was strongly influenced by nuclear weapons development and nuclear energy, Europe has long-standing experience, including industrial radium production, which started in Germany and Bohemia before World War I, with Europe being the largest producer between the World Wars. and uranium mining after World War II in countries such as France, the Czech Republic, Norway, and Germany. These activities contributed to the development of expertise in natural radioactivity. Research on NORM in industries like phosphate production began in the 1960s.

The current (EU) European economy is strongly dominated by services. In Figure 11-2 the sectoral structure of employment is shown. Data on the Gross Domestic Product (GDP) provides a similar picture: more than 2/3 of the European Economy comes from the service sector. The manufacturing industry, including construction, accounts for less than 30%. Agriculture is only a minor part of the European economy.

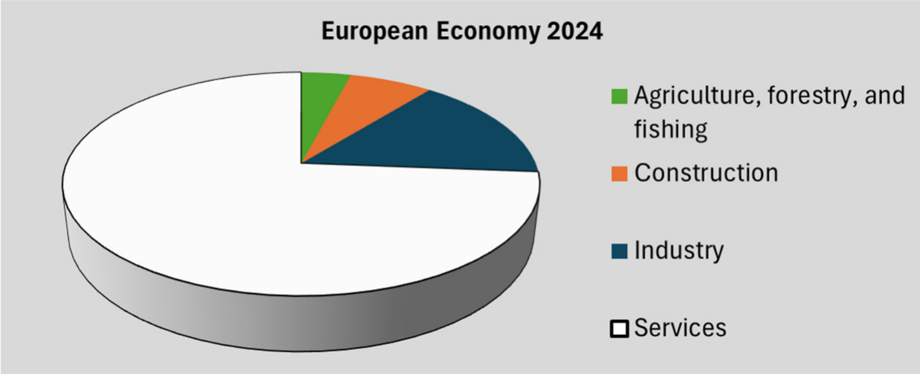

FIGURE 11-2: SECTORAL STRUCTURE OF EMPLOYMENT (SHARE OF TOTAL EMPLOYMENT, EU, 2024)

Although the manufacturing industry in Europe accounts for only a small share of GDP, it still includes large companies. These include companies that can be classified as part of the industries involving NORM.

There is significant oil and gas production in the North Sea. There are titanium dioxide production sites in Germany, France, the U.K., Norway, Finland, Italy, Spain, and the Czech Republic. In 2023, Europe (with EU, Russia, Ukraine, and the UK) was the continent with the second-largest steel production after Asia. There is also a production of non-ferrous metals, such as aluminum, copper, zinc, and lead. In particular, in eastern and south-eastern Europe, coal mining is an important mining sector. Industries dealing with zirconium sands or oxides (manufacturers of ceramics and refractories, foundries,…) are widespread, and groundwater treatment is the prevailing technique for drinking water production. During the last 10 years, the development of geothermal energy has opened a new field of investigation for NORM.

Radiation protection across Europe is strongly influenced by the EU Basic Safety Standards (BSS), even in non-EU countries. The 1996 EU BSS already addressed the issue of industries dealing with NORM, which triggered various studies and meetings, as well as the first efforts in different EU Member States to develop national inventories of activities involving NORM. These NORM regulations were extended with the publication of the European BSS of 2013 [176]. The 2013 BSS – based on ICRP 103 and IAEA standards – expanded these regulations. Because the Member States of the EU retain national sovereignty, EU directives are implemented differently at the national level, reflecting country-specific conditions, including in radiation protection and occupational safety. Some regulations, however, such as the Construction Products Regulation177, apply directly across all EU Member States.

The EU BSS regulates the following fields with potential exposures:

- Human activities that involve natural radiation sources, which may cause a significant increase in the exposure of workers or members of the public, in particular.
- The processing of materials with naturally occurring radionuclides.
- External exposure from building materials and consumer products containing naturally occurring radionuclides.
- Areas contaminated due to activities involving NORM.

Next to the EU BSS, there are other European regulations that may be relevant for NORM, such as the hazardous goods regulations for transport (ADR, see Chapter 8).

The Organization of the Heads of the European Radiological Protection Competent Authorities (HERCA) is a platform where national authorities work together "in order to identify common significant radiation protection issues and propose harmonization and/or practical solutions towards a common approach for these issues, whenever possible." [178]

Most European countries have professional societies for radiation protection specialists. These societies are generally also members of the IRPA. Regional conferences organized by the IRPA facilitate the exchange of information among radiation protection practitioners.

Practitioners and experts working professionally in radiation protection for NORM have founded the European NORM Association (ENA) and an analogous organization for radiation protection of radon (ERA). These organizations primarily serve the exchange of experience at the practitioner level.

In the following sections, the experiences gathered during the practical work as radiation protection professionals in European countries are briefly summarized. The statements are partly based on two surveys conducted by the IRPA TG on NORM, published in [179] and [52].

11.3.2 Application of the concepts of exemption and clearance to the regulation of NORM

The national implementation of the EU BSS has resulted in

- different positive lists on practices and/or residues,
- different exemption and clearance values,
- different concepts for the release of residues from monitoring under the radiation protection law,
- different requirements on the control of discharges from NORM-processing industries.
- different standards for the assessment of radon.

The HERCA Working Group on Natural Radiation Sources conducted a survey on how member states interpret, transpose, and apply EU BSS provisions on NORM exemption and clearance. The results, summarized in a 2021 report [**Error! Bookmark not defined.**], illustrate that a common regulatory framework (EU BSS) may result in differences in national implementations:

- The transposition of the EU BSS has resulted in a wide adoption of the general exemption and clearance level of 1 Bq/g for uranium and thorium series and 10 Bq/g for K-40; however, some countries made different provisions (see Chapter 7 and Case example France in Section 11.2.4).
- There are also differences between countries on how to apply (or not apply) the sum rules in the case of a combination of different NOR.
- Next to activity concentration-based criteria, most countries allow exemption of practices involving NORM on a case-by-case basis if compliance with a dose criterion is demonstrated. However, for public exposure, this dose criterion differs between countries, ranging from 0.01 to 1 mSv/a. Moreover, there are differences in

approaches to dose assessment: e.g., some countries require the drinking water pathway to be included in long-term dose assessment, while others don't.

- Very few countries have implemented operational criteria (such as dose-rate or surface contamination level) in their regulations to verify compliance with clearance. Several countries, however, accept the use of operational criteria when approved in an authorization process.
- About half of the countries have implemented the option of specific exemption and clearance, for instance, for materials involving K-40, for the maintenance of clinker ovens, or for disposal of material contaminated with Pb-210 and Po-210.
- Approaches differ between countries on whether NORM waste is classified as radioactive material supervised by the radiation protection authorities or even as radioactive waste. While in the first case, disposal in landfills under specific conditions is common, the second case requires disposal in the same manner as radioactive waste from nuclear facilities. The example of the French regulations in Section 11.3.4 shows that both ways are possible in one country.
- Reuse and recycling of NORM is a challenge everywhere, with only a few successful examples of reuse/recycling practices. More details on the treatment and disposal of NORM waste in Europe are given in Chapter 7.
- Some countries, but not all, have a specific approach regarding atmospheric or liquid discharges of NORM. It may be based on activity concentration, total activity discharged, a dose criterion, or a combination of these criteria. An extreme case is Norway. where the discharges require authorization if the total activity discharged in a year exceeds the total activity amount for moderate amounts, according to the IAEA GSR 3 [5] standards. These values are in the order of a few kilo-Becquerel, and this amount is so low that each large facility, including municipal wastewater treatment plants, is exceeding the limits [105].

11.3.3 Some challenges

The various national implementations of the European BSS have little effect on the industries at the national level. The main challenges arise in transboundary shipments of NORM, whether as commodities or waste.

- Due to national differences in applying exemption and clearance, a material or waste that complies with the exemption or clearance criteria in a given country may not be exempted or cleared in another country.
- This may be a significant obstacle for the reuse or recycling of NORM residues: for instance, a producer of titanium dioxide in Belgium wants to export for reuse residues from its production to a company located in Germany. While the Belgian authority may issue an authorization for the reuse of the material in Belgium, it is not competent to authorize the reuse in Germany. The producer of the residue should then go through a similar authorization process in all countries where it intends to export the residue. One should note, however, that this problem is not specific to radioactivity. In general, "end-of-waste criteria" are defined at the national level, and producers of residues need to check whether the residues will not be considered waste in all countries of export.
- While many countries do not allow the import of radioactive material as waste for disposal, the import for treatment, decontamination, or recycling is generally possible.

In practice, however, this runs into obstacles, especially regarding the approach to the secondary waste generated by the decontamination process. Some countries demand that the secondary waste be sent back to the country of origin for disposal, while other countries accept keeping the secondary waste for disposal in the country of destination.

- Regarding consumer products containing NORM, the approach also differs from one country to another. The importer of a consumer product who was authorized to sell its product in Belgium needed to apply for a similar authorization in all European countries for which the product was intended (see chapter on consumer products).

Certification systems and criteria for radiation protection experts vary between countries, preventing a unified European market for service providers. Additionally, not all countries have specific certification for NORM expertise, so experts without relevant knowledge may sometimes assess NORM-related activities.

11.3.4 Case example: France

What is the (general) regulatory status?

The following case example describes the specific regulations for NORM in France. This example demonstrates how national regulations interpret a regulatory framework, such as the European Directive 2013/59/Euratom, in the EU.

List of industries with NORM in French regulation

French regulation ("*Code de l'environnement*") contains a list of industrial sectors where NORM may be present. This list is based on Annex VI of Directive 2013/59/Euratom, transposed into the French regulation with some national specifications (*marked in italic*):

- rare earth extraction from monazite, rare earth treatment, *and production of pigments containing it*;
- production of thorium compounds, manufacture of products containing thorium, and mechanical work of such products;
- treatment of niobium/tantalum and aluminum ore;
- oil and gas production, *excluding research drilling;*
- production of geothermal energy, *excluding small-scale geothermal energy;*
- production of titanium dioxide pigments;
- thermal production of phosphorus;
- zircon and zirconium industry, *including the refractory ceramics industry*;
- production of phosphate fertilizers;
- cement production, including maintenance of clinker ovens;
- coal-fired power plants, including boiler maintenance;
- production of phosphoric acid;
- production of primary iron;
- tin, lead, or copper *foundry activities*;
- treatment by filtration of groundwater *circulating in magmatic rocks*;

- *extraction of natural materials of magmatic origin, such as granitoids, porphyries, tuff, pozzolane, and lava, when intended for use as building products.*

The industries concerned are subject to a certain number of measures, in particular a radiological characterization, as is done in many countries. On the other hand, if the authorities suspect the presence of natural radioactivity at a level that cannot be disregarded from a radiation protection perspective, the regulatory arsenal can be activated for a specific activity, even if it is not on the list.

French authorities have prioritized the industries on this list based on worker and population exposure, particularly for inspection purposes. Priority 1 focused on the production of thorium compounds, the production of products containing thorium, the mechanical processing of products containing thorium, and thermal establishment (focus on tartar deposits in thermal water transport pipes).

Identification of the industries on this list

Despite some surveys in particular sectors (linked to rare earths or thermal establishments), no exhaustive identification of the facilities concerned has yet been carried out. According to estimates, nearly 1,000 companies could be concerned.

This identification was recently highlighted as a subject of interest for the coming years, permitting better planning of the inspection program and the management of residues and waste containing NORM.

Distinction between "NORM" and "SRON"

In French regulation, a distinction is made between "NORM" and "SRON" ("*substances radioactives d'origine naturelle*"): SRON are NORM for which the K-40 or one or more radionuclide from the decay chains of U-238 and Th-232 have a mass-related activity concentration greater than the exemption values. The values are the same as defined in the European Directive (1 Bq/g for U-238 and Th-232 decay series; 10 Bq/g for K-40). The *value 1 Bq/g applies to each radionuclide in the decay chain (by default, all radionuclides in a chain are considered to be in equilibrium).*

This distinction NORM/SRON has some practical importance. If, after characterization, the mass-related activity concentrations of a material are below the exemption values, it is considered that there are no radiation protection issues (there are therefore no specific regulatory provisions), with the exception of sectors such as building materials, where regulations apply even if the values are below the exemption values. In a similar way, exposure to natural materials in products, below the exemption values, is not explicitly covered in Directive 2013/59/Euratom; a legal uncertainty remains.

If, on the other hand, a material classified SRON is used in industrial activities, the practice is considered a nuclear activity, with all the associated regulatory constraints, in particular the application of the Labor Code to workers in the installation (therefore, an assessment of the radiological risk to workers is required).

Regulations to be applied in the presence of SRON

The exposure limit values defined in the French regulation agree with the European standards (Directive 2013/59/Euratom).

Exposure studies for workers are carried out by considering all exposure routes (external irradiation, ingestion, and inhalation of dust, except radon). From this, the individual and collective protection measures to be put in place are derived. The measures must yield that finally no internal exposure to the workers occurs.

As the principle of limitation must always be coupled with the principle of optimization, actual doses must ultimately be as low as reasonably possible.

If workers have to be classified (A or B, see above), management will be carried out in the same way as for a planned exposure situation, with the implementation of a radiation protection organization, risk reduction measures, the definition of dose constraints, radiological zoning, training, exposure monitoring, etc. If there are (measurable) discharges, then discharge authorizations will be required. Then it is periodically checked that the protection is adequate (at the workstation, individually, etc.) and is consistent with the optimization principle.

If the previous values are not exceeded for the worker (to be checked periodically), then there are no specific provisions required (but in this case, no notion of existing exposure situation).

The radon risk is dealt with in parallel, with a reference level associated with its annual average activity concentration in air of 300 Bq/m³. For workers operating in radon zones, the dose assessed is added to the effective doses obtained from dosimetric monitoring results for other exposures to ionizing radiation.

Facilities with SRON in quantities exceeding 1 ton (1 Mg)

Nuclear activities involving materials containing SRON are subject to a specific regime governing "facilities classified for environmental protection" ("*installations ICPE*") when the quantity of material held exceeds 1 tonne. On this point, national regulations are consistent with IAEA standards and guidelines and Euratom Directive 2013/59, except for the mass criterion, which is specific to French regulations.

Materials and residues from these facilities can't be used for the manufacture of consumer goods or construction products. Residues may, where appropriate, be recycled in the process specific to the activity or disposed of in specific waste storage facilities.

Regulation relative to particular uses of NORM in construction materials and products

French regulation prohibits the addition of radionuclides and the use of radioactive substances of natural origin (SRON) in consumer goods and construction products (also a ban on the import of such products). *In this case, French legislation is therefore more restrictive than the Euratom directive requires; the legislation of other countries does not mention SRON in the prohibitions on practice.*

Gamma radiation emissions from construction materials and products used in buildings must be checked before they are placed on the market (subject to specific regulations since 2018). The strategy is based on measuring activity concentrations of U-238, Th-232 (and their decay products), and K40. It involves calculating an 'activity concentration index' (I), which is used as an indicator of compliance with a reference level of 1 mSv/year for persons inside buildings (in addition to natural exposure outside buildings). This strategy, based on the European Commission's recommendations published in 1999, was introduced in Directive 2013/59/Euratom and in IAEA Guide GSG-8 and SSR 117. An indicative list of the materials concerned has also been published.

The conditions for the use of construction materials and products when the calculated I index exceeds 1 have not yet been defined in the regulation.

The accreditation system for laboratories required to measure the concentration of natural radionuclides used to calculate the activity concentration index (I) was established in 2019.

Producers of materials and manufacturers of construction products, in particular in the field of concrete products, are aware of NORM.

According to concrete professionals, recycling (NORM reuse) remains limited in France compared to other countries (for example, the reuse of fly ash in concrete). However, research is being conducted in France by certain manufacturers.

Regulation relative to particular uses of NORM in fertilizers

Exposure to natural radionuclides in non-food products and goods, excluding construction materials, is not subject to specific regulatory oversight (apart from the ban on the addition of SRON). No exposure reduction strategy has been provided for in the regulations.

A French expert group recently recommended that prospective studies be carried out to characterize the natural radioactivity of fertilizers and agricultural amendments and to assess the risk to people who handle them.

Particular case: focus on phosphogypsum management

In the 1980s, France produced around 7 million tonnes of phosphogypsum (generated during the production of phosphoric acid for use in phosphate fertilizers and foodstuffs). Until the 1990s, the discharge of phosphogypsum into the sea or rivers was common practice; that is why all the industrial sites that generated phosphogypsum do not host a stockpile.

Directive 2008/98/EC of the European Parliament and of the Council on waste was transposed into French law in 2020. It clarified the definition of waste, waste producer, and waste holder, prevention, reuse, recycling, and recovery, and defined the main stages in waste management by hierarchizing them as follows: prevention, reuse, recycling, recovery, and disposal. It introduces the possibility for certain substances to be removed from waste status once they have undergone appropriate treatment. It required waste producers and holders to characterize their waste. The text introduced a system of administrative penalties. Where appropriate, if the producer or holder of the waste cannot be identified or is insolvent, the State may, with the possible financial assistance of the local authorities, entrust the management of the waste and the restoration of the site polluted by this waste to a competent public body.

French phosphogypsum stockpiles were set up before the Waste Directive and its transposition into French law came into force. However, it should be noted that the recovery of phosphogypsum in the form of plaster or as road fill is consistent, in principle, with the hierarchy of waste treatment methods, which favors recovery over disposal where justified. From a practical point of view, however, the recovery of these materials appears incompatible with their classification as hazardous waste in accordance with the Commission Decision[22] of 3 May

[22] replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste (notified under document number C(2000) 1147) (Text with EEA relevance) (2000/532/EC)

2000. According to this classification, phosphogypsum must be disposed of in a hazardous waste disposal facility (ISDD), classified as an ICPE. Discharge into the sea or river, as practiced in the past, is also incompatible with this classification.

Particular case: management of a situation involving potassium chloride

In February 2024, the gantry at a waste disposal site in France was triggered by the KCl contained in a product used to make infant milk. This event highlighted the fact that KCl, as a raw material, may have a K40 concentration exceeding 10 Bq/g due to its concentration in the dehydrated product. So, it is considered as a "SRON" and French regulation is prohibiting its use in consumer goods.

The potassium in the body is regulated by a homeostatic mechanism. This raises the question of whether an excess intake of potassium leads to an additional dose. IRSN proposed to the French authorities to revise French regulations to allow the use of compounds naturally containing potassium in the manufacture of foodstuffs.

Practical experiences

Are the authorities aware of NORM?

Yes, they are. However, only a few people are working on this subject, dispersed among different authorities. Even within the same authority, people working on this subject are not in the same department (no unit dedicated to it).

Are the companies aware of NORM?

Some companies are aware of NORM, but they represent a small share of those concerned (no particular culture of radiation protection). Work has started to raise their awareness (by the authorities and IRSN), especially during inspections. But as there are relatively few of them, there's still a lot of work to be done.

What role do RP societies (and IRPA as their international network) play?

They help maintain a level of knowledge about the subject NORM and share the issues encountered across different countries.

11.4 North America (USA and Canada)

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11.4.1 General information

The United States and Canada have a long history of managing and disposing of NORM, starting with radium mining as early as 1896 in Colorado [1]. Some of the carnotite ore Madame Curie worked with came from southwest Colorado mines.

No single, comprehensive federal NORM statute or regulation exists; instead, coverage is agency by agency, medium-by-medium and sector-by-sector.

11.4.2 USA

Over the decades, numerous U.S. industries have been identified as being impacted by NORM. According to the U.S. Environmental Protection Agency (EPA), they include [2]:

Mining

- Hard Rock Metal Mining
- Rare Earths Mining Wastes
- Uranium Mining Wastes
- Copper Mining and Production Wastes
- Bauxite and Alumina Production Wastes
- Energy production
- Oil and Gas Production Wastes
- Coal Combustion Residuals
- Water treatment
- Drinking Water Treatment Residuals
- Wastewater Treatment Residuals
- Consumer products
- Fertilizer and Fertilizer Production Wastes
- Cigarettes
- Building Materials
- Granite Countertops

Note that the U.S. does not have an official "positive list" as recommended by IAEA. Lists that are in statute or regulation can become hard to update.

It should be noted that there is no definition of NORM (or TENORM) in EPA regulation (just guidance) [3]. The U.S. uses the term TENORM, whereas IAEA et al. use NORM. There is an inconsistency among definitions. The States use a definition that limits TENORM to materials that have been concentrated through processing (EPA includes sources that have been relocated that could cause an exposure). A thorough review of the status of NORM regulation and differences between NRC and EPA approaches were conducted by the National Research Council in 1999 [4]. Unfortunately, not much has changed in 25 years.

States have the authority to regulate and control all forms of radiation and radioactivity, not reserved to the federal government, through their respective Radiation Control Acts [5]. Also, Article X of the Bill of Rights to the U.S. Constitution states that only that which is specifically reserved to the federal government stays federal; otherwise, it goes to the states or the people.

The hierarchy in the U.S. relative to NORM is that Congress makes the laws that grant authority to various Executive agencies to regulate. Federal law overrides State law; however, federal authority is often delegated to the states for implementation (e.g., solid waste programs). The state has police authority to protect public health and safety. State law that is contrary to federal law would be invalid. But state law can go beyond federal law if not contrary. States, of course, have stepped in to regulate NORM on different levels [6].

In 1978, the AEA was amended to regulate uranium and thorium mill tailings by generally applicable standards promulgated by EPA that DOE and NRC implement, but not other mine wastes, including radioactivity (e.g., vanadium or radium tailings from the same ore) [7]. This was not about controlling releases from NORM outside the fuel cycle. Mill tailings are part of the fuel cycle, so they were regulated. Uranium mining and milling are separate from other NORM industries only because of the security issues surrounding the fission process under the AEA, not safety.

Oil and gas development in the Gulf States (both onshore and offshore) in the early 1970s brought the NORM issue of radon in natural gas forward, both as a safety and environmental issue [4][8][9]. Industry resistance in many sectors has been the standard for many decades. There are legislative and regulatory gaps for NORM at the federal level that preclude a consistent approach across the U.S. [#].

Adding to the legislative patchwork, EPA was granted authority under a variety of statutes to address environmental pollution. In 1986, radioactivity was declared a known human carcinogen by EPA under the Clean Air Act [12], which has regulatory authority over hazardous air pollutants, including radioactivity.

The following statutes have a nexus with radioactive materials, including NORM, under the authority of the EPA:

- Clean Air Act (CAA) (42 USC 7401 et seq.)– radionuclide air emissions
- Safe Drinking Water Act (SDWA) (42 USC 300f et seq.)– radionuclides in public water
- Clean Water Act (CWA) (33 USC 1251 et seq.)– radionuclides in discharges/effluents
- CERCLA (Superfund) (42 USC 9601 et seq.)– cleanup of radioactive sites
- Resource Conservation and Recovery Act (RCRA)- (42 USC 6901 et seq.) waste management and disposal
- AEA-UMTRCA

After decades of neglect from state and federal agencies, uranium mill tailings were regulated as a new category of byproduct material – 11e.2 named after the location in the AEA definitions. It listed cleanup standards for both active and inactive mills and vicinity properties, along with numerous other provisions (indoor gamma and radon limits). It is the one statute where the radiological and nonradiological components are regulated under the same law. The cleanup standard of 5 pCi/g (0.185 Bq/g) of Ra-226 averaged over 100 m^2 and 15 cm depth has been used in numerous other situations involving NORM; however, it should be noted that the standard is 40 years old and would not be adopted using today's dosimetry.

It is a misnomer to state that there are no federal regulations that apply to NORM. There are no federal disposal standards, no requirements that would be necessary if under a radioactive materials license. But these statutes are the basis for the regulation of NORM (usually along with manmade radionuclides).

This is the basis for the divide between licensed (i.e., planned situations) and those regulated under environmental statutes that are performance-based (generally considered existing situations). It may be that there are too many regulators of NORM, none of whom have full authority.

Most NORM is managed and regulated at the State level. About a dozen states have some NORM regulations based on the Conference of Radiation Control Program Directors (CRCPD) Part N suggested state regulation [13]. It adopted the general/specific license approach taken from planned activities. This is where state licensing commitments, requirements, exposure, and dose limits, and numerous safety and environmental requirements (along with financial assurance). The states do not have the resources, manpower, and expertise to effectively control these industries and residuals without a consistent baseline and clear authority to regulate. Some states are now requiring registration and notice in lieu of licensing. The temptation of a race to the bottom is real since these materials are in commerce.

The Part N framework was originally designed to address issues with the oil and gas industry and phosphogypsum. That framework is stressed with the increased volumes and concentrations now encountered due to hydrofracking and increased activity in mining due to the need for critical minerals. Agencies and states use different dosimetry, so different dose conversion factors may be used. EPA uses risk instead of dose, which introduces additional challenges.

The federal-state division between AEA materials and other agencies and states responsible for the remainder is the result of Cold War security controls over fissile material, is outdated, and not effective for controlling occupational and public exposure from sources and practices involving NORM at the federal level. Some practices have been identified and regulated. Without a federal baseline, states are taking a variety of approaches to NORM that have led to expensive lessons learned and liabilities that the safety standards do not address. IAEA GSR-1 [2] discusses the requirements for legislative and regulatory minimum suggested requirements.

The NCRP publishes recommendations much like ICRP does. The most recent Radiation Protection Guidance for the United States is from 2018 [#&]. It adopts most of ICRP 103 with a few modifications. It expands the scope to all types of controllable radiation, adopts the situational approach that is appropriate for the situation, and makes recommendations for exposure guidelines [#&]. It also adopts the ethical recommendations from ICRP Report 138 [#&].

The regulatory agencies have not adopted Report 180. NCRP also published a Commentary on TENORM in the Oil and Gas Industry that calls for a full investigation and report [17]. NCRP also published a report on TENORM in the mineral extraction industry in 1993, that is still very useful [18].

States continue to take the lead work to protect public health and the environment and provide a level playing field for industry. This will not be easy, as states have to balance their budgets every year and lack sufficient presence in the field. Part N is under revision and will be the benchmark that states can follow without relying on federal authority. It is anticipated to be similar to NCRP recommendations, along with a graded and holistic approach following ICRP 142 [19].

Due to the lack of consistency among agencies, states, the courts and the legislature, there is a legislative gap at the highest level of radiation control for NORM. As such, the current lack of federal oversight in the U.S. is not consistent with the requirements of IAEA GSR-1.

11.4.3 Canada

Canada also has a long history of uranium mining and milling as well as oil and gas development. The Canadian Nuclear Safety Commission (CNSC), formerly the Atomic Energy Control Board (AECB), has legislative control of nuclear fuel cycle materials and man-made radionuclides. However, naturally occurring radioactive material (NORM) is exempt from CNSC jurisdiction except for the import, export and transport of the material. Therefore, jurisdiction over use and radiation exposure to NORM rests with each Canadian province and territory [20].

The Federal Provincial Territorial Radiation Protection Committee (FPTRPC), a Canadian intergovernmental committee established to support federal, provincial and territorial radiation protection agencies in carrying out their respective mandates, recognizes that the potential radiation hazards from NORM are the same as those from radioactive materials controlled by the CNSC. The basic principle of these guidelines is that *where workers or the public are exposed to additional sources or modes of radiation exposure because of activities involving NORM, the same radiation protection standards should be applied as for CNSC regulated activities* [Emphasis added]. This applies to situations where NORM is in its natural state and to cases in which the concentration of NORM material has been increased by processing [20].

The *Canadian Guidelines* set out principles and procedures for the detection, classification, handling and material management of NORM in Canada, and also include guidance for compliance with federal transportation regulations. These *Guidelines* provide the framework for the development of more detailed NORM management practices and guidelines by regulatory authorities, affected industries and specific workplaces.

Uranium mines and mills are regulated and licensed by the Canadian Nuclear Safety Commission (CNSC) (i.e., planned situation in current vernacular). The CNSC's licensing process for uranium mines and mills follows the stages described in the Uranium Mines and Mills Regulations. The CNSC uses a lifecycle approach to licensing, issuing licences for all phases in the lifecycle of a uranium mine and mill. In addition, uranium mines and mills are also subject to applicable environmental review requirements. In addition, uranium mines and mills are also subject to applicable environmental review requirements.

The development of rare earth element (REE) production in Canada could generate significant economic benefits but also poses serious potential risks to the environment [21]. The health risks associated with REE mining are currently understudied, and the industry lacks regulations or best-practice guidance to protect workers against these unique health hazards. As a result, risks in REE mining are likely underestimated or even overlooked. The early assessment of risks and the adoption of best practices to limit harmful exposures will help contribute to the safe and responsible extraction of REEs required for the clean energy transition [22].

11.5 Insights of Radiation Protection in NORM-Related Industries in Latin American Countries

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11.5.1 Introduction

The Latin American countries included in this chapter are Argentina, Brazil, Colombia, Cuba, México, Paraguay and Perú, as these countries are actually involved in a project of the Ibero-American Forum of Radiological and Nuclear Regulators (FORO) for the development of a guide for NORM characterization. Other countries as Spain and Portugal also participate in the FORO project, but they are excluded from this chapter as they are represented by the European regional chapter.

During 2021, in order to define the scope of the project, Colombia, on behalf of FORO, conducted a survey within the countries to assess the situation regarding NORM management. The key findings from the survey and main aspects that are being discussed in the guide under development form the basis of this chapter.

The main industries identified in the region related to NORM are mining, metal production, and oil and gas activities. Half of the countries reported a lack of a specific regulatory framework for these industries, with very few countries having a complete, specific regulatory framework, including strategies for residues and waste management. Some countries in the Latin American region consider NORM management in the framework of existing exposure situations.

Another issue identified was the need of policies that clarify the roles of the different authorities involved and the coordination between them, so that regulatory control can be comprehensive and efficient, avoiding overlapping of competencies.

Regarding infrastructure, half of the countries declared have their own analytical capacity, identifying the need for equipment, human, and economic resources to address NORM management effectively.

The survey highlighted the need to have a harmonized guidance on characterization, as a crucial step that allows an assessment of the potential radiological impact on both people and the environment, providing clarity and a basis for the decision-making process by understanding the situation and risks involved by these industries. This guide is expected to help countries assess their national situations and develop appropriate regulatory strategies that align with a graded and integrated approach.

Main aspects considered by the region

- The importance of understanding the relationship between natural sources such as rocks, soils, minerals, which contain natural radionuclides, from the regulatory definition of radioactive material, to clarify when a material should be designated as radioactive by the national legislation or a regulatory body due to its radioactivity. It is important to distinguish the scientific definition from the regulatory one.
- The critical role of an appropriate legal and regulatory framework to implement policies and strategies for the safe management of NORM, within an integrated approach.
- The importance of having under regulatory control those industrial processes that could present relevant risks to workers, members of the public and the environment, to avoid over–regulation.
- The reasonability of the approach to control activities, which should be practical, gradual, reasonable, and flexible enough to achieve effective regulation that protects workers, the public, and the environment without unnecessarily restricting the activities

of industries associated with NORM. The regulatory approach should balance between the different hazards, by relying on multi-expertise teams (experts on conventional, environmental and radiological risks).

- The collaborative approach between authorities and companies should work in a close dialogue.
- The recognition of characterization as a fundamental step to, first, know and understand the national scenario, in terms of both, the number of facilities and the risks associated with them, to be able to decide what degree of control to apply to the facilities and activities.
- The importance of using the appropriate sampling strategy and sampling methods to obtain representative samples and perform an adequate monitoring. Also includes laboratory techniques for the direct or indirect determination of radionuclides in the different materials generated and in environmental matrices. Characterization involves also assessing the effective dose of workers and members of the public taking into account the different exposure scenarios and the protection measures against conventional hazards already implemented in place by the industries.
- The convenience of implementing screening values to assess the risk applying graded approach concept. These conservative values could be validated through appropriate statistical correlations or defined based on dose criteria. Depending on the situation, screening values could be adopted, in terms of dose rate (scrap metal), activity concentration or activity concentration per area. This could facilitate the practical management of materials.
- The region also considers the importance of defining the minimum capabilities needed for the staff involved in the radiological characterization, for operators, TSOs and regulatory authorities, defining the radiation protection training for this specific task and the process for authorization of this capacity.
- The importance of applying tools such as conditional clearance to treat NORM waste as conventional waste and not as radioactive waste.

11.5.2 Challenges identified

Many countries reported the need to establish policies and a strategy at the governmental level to allocate responsibilities of the various authorities involved and to have a specific regulatory framework for NORM.

The region identified staff training needs (regulatory and technical aspects) regarding NORM as a primary need, and an adequate infrastructure to carry out the characterization of materials and workplaces.

It was identified that the need to expand collaboration between regulatory authorities and research centres, private laboratories and universities to cover the need for measurements and dose assessments.

In order to implement reuse and recycling of NORM residues, countries of the region need to develop adequate and coherent regulatory frameworks, supported by feasible technological solutions and clear authorization criteria, taking into account economic and social aspects. It is needed to develop technical options, where options could be attractive if there is a strong economic incentive to use (NORM) residues, being clue the social acceptability by the public.

Decommissioning activities in the future regarding NORM activities challenge and reinforce the need for the region to strengthen a harmonized regulatory, technical, and radiological protection approaches discussed above.

11.5.3 Conclusions

The survey, conducted at FORO, was an important tool for understanding the main characteristics of the Latin American region regarding the management of NORM. As a result of main findings, the FORO approved the project for the development of the guide of NORM Characterization for the region, that is planned to be published by the end of 2026, with the objective to provide harmonized criteria and guidance to know the magnitude of the situation in each country to determine the level of control to be implemented.

The countries of the region consider this characterization guide as a starting point to initiate actions aimed at establishing and strengthening the necessary infrastructure for the safe management of industries involving NORM, while other topics could be considered as potential projects to be developed in the future.

11.5.4 References

- "Guía para la caracterización de industrias y actividades vinculadas con NORM: un enfoque a las industrias del gas y el petróleo y la minería." Ibero-American Forum of Radiological and Nuclear Regulators (FORO), under development.

- Position paper sobre gestión de radionucleidos naturales (FORO), IRPA XII Congreso regional de seguridad Radiológica y Nuclear, 23 al 27 de octubre de 2022 Santiago, Chile

12 APPENDIX – USEFUL DATA FOR PRACTITIONERS

Table 12-1: Half-lives, decay modes and decay energies

		T1/2		**Data from Ivanovich/Harmon 1992**			
	□			Energy	w	Energy	w
	□			keV	%	keV	%
U-238	α	4.40E+09	a	4195	77	4147	23
Th-234	β	24.1	d	199	72.5	104	17.8
Pa-234m	β	1.18	min	2290	98.4	1.25	0.74
Pa-234	β	6.7	h	530	66		
U-234	α	2.50E+05	a	4768	72	4717	28
Th-230	α	7.50E+04	a	4682	76	4615	24
Ra-226	α	1600	a	4781	94.5	4598	5.5
Rn-222	α	3.82	d	5486	100		
Po-218	α	3.05	min	6110	100		
Pb-214	β	26.8	min	1030	6		
Bi-214	β	19.7	min	3275	19.9	1880	7.18
Po-214	α	1.60E-04	s	7830	100		
Pb-210	β	22.3	a	17	81	63	19
Bi-210	β	5	d	1161	99		
Po-210	α	138.4	d	5305	100		
	□						
Th-232	α	1.40E+10	a	4007	76	3952	24
Ra-228	β	5.8	a	39	60	15	40
Ac-228	β	6.1	h	2180	10	1110	31
Th-228	α	1.9	a	5421	71	5338	28
Ra-224	α	3.7	d	5684	94.5	5447	5.5
Rn-220	α	55.6	s	6296	100		
Po-216	α	0.146	s	6777	100		
Pb-212	β	10.6	h	569	12	331	83
Bi-212	α	60.5	min	6090	30	6050	70
Bi-212	β			2248	86.6	1521	6.8
Po-212	α	3.00E-07	s	8780	100		
Tl-208	β	3.1	min	1800	51	1290	22.8
	□						
U-235	α	7.00E+08	a	4391	57	4361	18
Th-231	β	25.5	h	305	35	218	37
Pa-231	α	3.30E+04	a	4999	25.4	4938	22.8
Ac-227	β	21.8	a	46	54		
Th-227	α	18.7	d	6036	23	5976	24
Ra-223	α	11.4	d	5714	53.7	5605	26
Rn-219	α	3.92	s	6813	81	6547	11
Po-215	α	1.80E-03	s	7384	100		
Pb-211	β	36.1	min	1355	92.4	525	5.3
Bi-211	α	2.16	min	6617	83	6273	17
Tl-207	β	4.79	min	1442	99.8		

K-40	β		α				

TABLE 12-2: REFERENCE PERSON COEFFICIENTS (nSv/h per MBq/m³) EPA 2025

Nuclide	Newborn	1-yr-old	5-yr-old	10-yr-old	15-yr-old	Adult
Tl-208	507.60	478.80	453.60	439.20	410.40	403.20
Pb-210	0.07	0.06	0.05	0.04	0.04	0.03
Pb-211	9.11	8.42	7.88	7.56	6.91	6.80
Pb-212	15.62	14.54	13.61	13.00	11.66	11.48
Pb-214	30.96	28.84	27.07	25.88	23.36	23.04
Bi-210	0.13	0.12	0.11	0.11	0.10	0.10
Bi-211	5.90	5.51	5.18	4.93	4.46	4.39
Bi-212	15.30	14.15	13.28	12.82	11.77	11.63
Bi-213	16.92	15.77	14.80	14.15	12.85	12.67
Bi-214	220.68	204.84	192.60	186.12	171.72	169.56
Po-210	0.00	0.00	0.00	0.00	0.00	0.00
Po-212	0.00	0.00	0.00	0.00	0.00	0.00
Po-214	0.01	0.01	0.01	0.01	0.01	0.01
Po-215	0.02	0.02	0.02	0.02	0.02	0.02
Po-216	0.00	0.00	0.00	0.00	0.00	0.00
Rn-219	7.31	6.80	6.41	6.12	5.51	5.44
Rn-220	0.09	0.08	0.07	0.07	0.07	0.06
Rn-222	0.05	0.05	0.05	0.04	0.04	0.04
Ra-223	14.44	13.39	12.53	11.95	10.73	10.55
Ra-224	1.22	1.14	1.07	1.02	0.92	0.91
Ra-226	0.79	0.74	0.69	0.66	0.60	0.59
Ra-228	0.00	0.00	0.00	0.00	0.00	0.00
Ac-227	0.01	0.01	0.01	0.01	0.00	0.00
Ac-228	123.84	114.48	107.28	103.32	94.68	93.60
Th-227	13.97	13.00	12.20	11.66	10.48	10.33
Th-228	0.18	0.17	0.16	0.15	0.13	0.13
Th-230	0.03	0.03	0.02	0.02	0.02	0.02
Th-231	0.87	0.77	0.71	0.67	0.59	0.58
Th-232	0.01	0.01	0.01	0.01	0.01	0.01
Th-234	0.61	0.55	0.50	0.48	0.42	0.41
Pa-231	4.00	3.71	3.47	3.32	2.98	2.94
Pa-234	204.48	188.64	176.76	169.92	155.52	153.72
Pa-234m	3.03	2.81	2.65	2.56	2.37	2.34
U-234	0.01	0.01	0.01	0.01	0.01	0.01
U-235	17.50	16.42	15.30	14.62	13.18	12.96
U-238	0.01	0.00	0.00	0.00	0.00	0.00

TABLE 12-3: TYPES OF MATERIALS, CLASSIFIED ACCORDING TO THEIR RATES OF ABSORPTION FROM THE RESPIRATORY TRACT INTO BLOOD

From ICRP 130 page 30

Type F is defined as deposited materials that are readily absorbed into blood from the respiratory tract (fast absorption). Type M is defined as deposited materials that have intermediate rates of absorption into blood from the respiratory tract (moderate absorption). Type S is defined as deposited materials that are relatively insoluble in the respiratory tract (slow absorption). Type V is defined as deposited materials that, for dosimetric purposes, are assumed to be instantaneously absorbed into blood from the respiratory tract (only certain gases and vapours; very fast absorption).

TABLE 12-4: ABSORPTION CLASSES OF NOR. (FROM ICRP 137. DOSIMETRIC DATA FOR …)

Nuclide	Typ F	Type M	Type S
Pb-210	Type Flead dichloride, dibromide, difluoride, hydroxide, nitrate, oxide, al unspecified forms		mineral dusts
Po-210		chloride, hydroxide, volatilized polonium, all unspecified forms	
Ra-226, Ra-228	nitrate	all unspecified forms	
Thorium	NB: Type F should not be assumed without evidence	thorium hydroxide	oxide, all unspecified forms
Uranium	uranium hexafluoride, UF6, uranyl tributyl-phosphate	uranyl acetylacetonate; depleted uranium aerosols from use of kinetic energy penetrators; vaporised uranium metal; all unspecified forms	

Thorium: Special type: Water-soluble forms, including thorium chloride, citrate, nitrate, and sulphate, thorium fluoride

Uranium: Intermediate Type F/M: uranyl nitrate UO2(NO3)2; uranium peroxide hydrate UO4; ammonium diuranate; uranium trioxide UO3. Intermediate Type M/S: uranium octoxide, U3O8; uranium dioxide UO2, Uranium aluminide UAlX

TABLE 12-5: INHALATION DOSE COEFFICIENTS (ICRP 137)

Nuclide	Lung absorption rate	fA	AMAD	e(50)	hT(50)
			(µm)	µSv Bq-1	µSv Bq-1
Pb-210	F	2.00E-01	0.3	0.38	0.037
Pb-210	F	2.00E-01	1	0.51	0.049
Pb-210	F	2.00E-01	5	0.71	0.067
Pb-210	F	2.00E-01	10	0.64	0.061
Pb-210	M	4.00E-02	0.3	1.2	0.032
Pb-210	M	4.00E-02	1	0.93	0.025
Pb-210	M	4.00E-02	5	0.62	0.016
Pb-210	M	4.00E-02	10	0.38	0.0095
Pb-210	S	2.00E-03	0.3	20	0.013
Pb-210	S	2.00E-03	1	15	0.0097
Pb-210	S	2.00E-03	5	9.2	0.0051
Pb-210	S	2.00E-03	10	5.1	0.0025
Pb-212	F	2.00E-01	0.3	0.11	0.0013
Pb-212	F	2.00E-01	1	0.18	0.0016
Pb-212	F	2.00E-01	5	0.3	0.0022
Pb-212	F	2.00E-01	10	0.26	0.0019
Pb-212	M	4.00E-02	0.3	0.15	0.0002
Pb-212	M	4.00E-02	1	0.1	0.00024
Pb-212	M	4.00E-02	5	0.094	0.00032
Pb-212	M	4.00E-02	10	0.064	0.00028
Pb-212	S	2.00E-03	0.3	0.16	0.000032
Pb-212	S	2.00E-03	1	0.11	0.000083
Pb-212	S	2.00E-03	5	0.094	0.00015
Pb-212	S	2.00E-03	10	0.062	0.00015
Bi-212	F	5.00E-02	0.3	0.022	0.000012
Bi-212	F	5.00E-02	1	0.023	0.000011
Bi-212	F	5.00E-02	5	0.028	0.000012
Bi-212	F	5.00E-02	10	0.021	0.0000095
Bi-212	M	1.00E-02	0.3	0.023	0.000003
Bi-212	M	1.00E-02	1	0.024	0.0000044
Bi-212	M	1.00E-02	5	0.029	0.0000064
Bi-212	M	1.00E-02	10	0.021	0.0000059
Bi-212	S	5.00E-04	0.3	0.023	0.00000089
Bi-212	S	5.00E-04	1	0.024	0.0000025
Bi-212	S	5.00E-04	5	0.029	0.0000048
Bi-212	S	5.00E-04	10	0.021	0.0000046
Bi-214	F	5.00E-02	0.3	0.0085	0.0000019
Bi-214	F	5.00E-02	1	0.01	0.0000021
Bi-214	F	5.00E-02	5	0.014	0.0000024
Bi-214	F	5.00E-02	10	0.01	0.000002
Bi-214	M	1.00E-02	0.3	0.0087	0.00000055

Bi-214	M	1.00E-02	1	0.01	0.00000078
Bi-214	M	1.00E-02	5	0.014	0.0000011
Bi-214	M	1.00E-02	10	0.011	0.000001
Bi-214	S	5.00E-04	0.3	0.0087	0.00000018
Bi-214	S	5.00E-04	1	0.01	0.00000044
Bi-214	S	5.00E-04	5	0.014	0.00000079
Bi-214	S	5.00E-04	10	0.011	0.00000077
Po-210	F	1.00E-01	0.3	0.37	0.057
Po-210	F	1.00E-01	1	0.31	0.051
Po-210	F	1.00E-01	5	0.28	0.047
Po-210	F	1.00E-01	10	0.21	0.036
Po-210	M	2.00E-02	0.3	2.3	0.027
Po-210	M	2.00E-02	1	1.6	0.021
Po-210	M	2.00E-02	5	1.1	0.015
Po-210	M	2.00E-02	10	0.63	0.0099
Po-210	S	1.00E-03	0.3	3.9	0.0012
Po-210	S	1.00E-03	1	2.8	0.00099
Po-210	S	1.00E-03	5	1.8	0.00072
Po-210	S	1.00E-03	10	1.1	0.00048
Ra-223	F	2.00E-01	0.3	0.16	0.01
Ra-223	F	2.00E-01	1	0.16	0.01
Ra-223	F	2.00E-01	5	0.19	0.012
Ra-223	F	2.00E-01	10	0.15	0.0098
Ra-223	M	4.00E-02	0.3	4.1	0.0025
Ra-223	M	4.00E-02	1	2.5	0.0024
Ra-223	M	4.00E-02	5	1.8	0.0025
Ra-223	M	4.00E-02	10	1.1	0.002
Ra-223	S	2.00E-03	0.3	5.2	0.00017
Ra-223	S	2.00E-03	1	3.2	0.00027
Ra-223	S	2.00E-03	5	2.2	0.00041
Ra-223	S	2.00E-03	10	1.3	0.00038
Ra-224	F	2.00E-01	0.3	0.12	0.0066
Ra-224	F	2.00E-01	1	0.11	0.007
Ra-224	F	2.00E-01	5	0.13	0.0079
Ra-224	F	2.00E-01	10	0.1	0.0067
Ra-224	M	4.00E-02	0.3	2.2	0.0015
Ra-224	M	4.00E-02	1	1.3	0.0016
Ra-224	M	4.00E-02	5	0.93	0.0019
Ra-224	M	4.00E-02	10	0.56	0.0016
Ra-224	S	2.00E-03	0.3	2.7	0.00018
Ra-224	S	2.00E-03	1	1.6	0.00036
Ra-224	S	2.00E-03	5	1.1	0.00062
Ra-224	S	2.00E-03	10	0.67	0.0006
Ra-226	F	2.00E-01	0.3	0.15	0.049
Ra-226	F	2.00E-01	1	0.15	0.05

Ra-226	F	2.00E-01	5	0.16	0.056
Ra-226	F	2.00E-01	10	0.13	0.047
Ra-226	M	4.00E-02	0.3	3	0.031
Ra-226	M	4.00E-02	1	2.1	0.025
Ra-226	M	4.00E-02	5	1.4	0.018
Ra-226	M	4.00E-02	10	0.84	0.012
Ra-226	S	2.00E-03	0.3	31	0.01
Ra-226	S	2.00E-03	1	23	0.0075
Ra-226	S	2.00E-03	5	13	0.0041
Ra-226	S	2.00E-03	10	7.3	0.0021
Ra-228	F	2.00E-01	0.3	0.36	0.046
Ra-228	F	2.00E-01	1	0.37	0.047
Ra-228	F	2.00E-01	5	0.41	0.053
Ra-228	F	2.00E-01	10	0.34	0.044
Ra-228	M	4.00E-02	0.3	2.5	0.18
Ra-228	M	4.00E-02	1	1.9	0.13
Ra-228	M	4.00E-02	5	1.2	0.073
Ra-228	M	4.00E-02	10	0.68	0.037
Ra-228	S	2.00E-03	0.3	50	0.15
Ra-228	S	2.00E-03	1	38	0.11
Ra-228	S	2.00E-03	5	23	0.057
Ra-228	S	2.00E-03	10	13	0.027
Ac-227	F	5.00E-04	0.3	78	2.9
Ac-227	F	5.00E-04	1	54	2
Ac-227	F	5.00E-04	5	33	1.1
Ac-227	F	5.00E-04	10	18	0.53
Ac-227	M	1.00E-04	0.3	59	2.1
Ac-227	M	1.00E-04	1	43	1.5
Ac-227	M	1.00E-04	5	24	0.77
Ac-227	M	1.00E-04	10	12	0.36
Ac-227	S	5.00E-06	0.3	150	0.45
Ac-227	S	5.00E-06	1	110	0.33
Ac-227	S	5.00E-06	5	65	0.17
Ac-227	S	5.00E-06	10	36	0.077
Th-227	F	5.00E-04	0.3	0.29	0.049
Th-227	F	5.00E-04	1	0.31	0.054
Th-227	F	5.00E-04	5	0.37	0.064
Th-227	F	5.00E-04	10	0.32	0.055
Th-227	M	1.00E-04	0.3	3.6	0.012
Th-227	M	1.00E-04	1	2.4	0.009
Th-227	M	1.00E-04	5	1.6	0.0055
Th-227	M	1.00E-04	10	0.9	0.0031
Th-227	S	5.00E-06	0.3	4.9	0.00056
Th-227	S	5.00E-06	1	3.3	0.00046
Th-227	S	5.00E-06	5	2.1	0.00036

Th-227	S	5.00E-06	10	1.2	0.00025
Th-227		5.00E-05	0.3	4	0.0095
Th-227		5.00E-05	1	2.7	0.0088
Th-227		5.00E-05	5	1.7	0.0083
Th-227		5.00E-05	10	1	0.0065
Th-228	F	5.00E-04	0.3	13	1.7
Th-228	F	5.00E-04	1	14	1.9
Th-228	F	5.00E-04	5	17	2.3
Th-228	F	5.00E-04	10	14	1.9
Th-228	M	1.00E-04	0.3	20	0.92
Th-228	M	1.00E-04	1	15	0.67
Th-228	M	1.00E-04	5	9.1	0.37
Th-228	M	1.00E-04	10	5.1	0.19
Th-228	S	5.00E-06	0.3	46	0.071
Th-228	S	5.00E-06	1	35	0.052
Th-228	S	5.00E-06	5	23	0.028
Th-228	S	5.00E-06	10	14	0.014
Th-228		5.00E-05	0.3	22	0.88
Th-228		5.00E-05	1	16	0.7
Th-228		5.00E-05	5	11	0.48
Th-228		5.00E-05	10	6.5	0.31
Th-230	F	5.00E-04	0.3	26	7.2
Th-230	F	5.00E-04	1	28	7.9
Th-230	F	5.00E-04	5	34	9.4
Th-230	F	5.00E-04	10	29	8
Th-230	M	1.00E-04	0.3	18	4.2
Th-230	M	1.00E-04	1	13	3.1
Th-230	M	1.00E-04	5	7.3	1.7
Th-230	M	1.00E-04	10	3.8	0.84
Th-230	S	5.00E-06	0.3	34	1.1
Th-230	S	5.00E-06	1	25	0.78
Th-230	S	5.00E-06	5	15	0.4
Th-230	S	5.00E-06	10	7.8	0.19
Th-230		5.00E-05	0.3	18	4.1
Th-230		5.00E-05	1	14	3.2
Th-230		5.00E-05	5	9.2	2.2
Th-230		5.00E-05	10	5.7	1.4
Th-232	F	5.00E-04	0.3	30	7.4
Th-232	F	5.00E-04	1	33	8.1
Th-232	F	5.00E-04	5	40	9.6
Th-232	F	5.00E-04	10	34	8.2
Th-232	M	1.00E-04	0.3	20	4.3
Th-232	M	1.00E-04	1	15	3.1
Th-232	M	1.00E-04	5	8.2	1.7
Th-232	M	1.00E-04	10	4.2	0.86

Th-232	S	5.00E-06	0.3	140	1.5
Th-232	S	5.00E-06	1	100	1.1
Th-232	S	5.00E-06	5	55	0.54
Th-232	S	5.00E-06	10	27	0.25
Th-232		5.00E-05	0.3	20	4.2
Th-232		5.00E-05	1	16	3.3
Th-232		5.00E-05	5	10	2.2
Th-232		5.00E-05	10	6.5	1.4
Pa-231	F	5.00E-04	0.3	78	18
Pa-231	F	5.00E-04	1	86	19
Pa-231	F	5.00E-04	5	100	23
Pa-231	F	5.00E-04	10	87	20
Pa-231	M	1.00E-04	0.3	50	10
Pa-231	M	1.00E-04	1	36	7.5
Pa-231	M	1.00E-04	5	20	4.1
Pa-231	M	1.00E-04	10	10	2.1
Pa-231	S	5.00E-06	0.3	120	3.4
Pa-231	S	5.00E-06	1	85	2.5
Pa-231	S	5.00E-06	5	46	1.3
Pa-231	S	5.00E-06	10	23	0.6
Pa-231		5.00E-05	0.3	49	10
Pa-231		5.00E-05	1	38	8
Pa-231		5.00E-05	5	26	5.4
Pa-231		5.00E-05	10	16	3.4
U-234	F	2.00E-02	0.3	0.35	0.32
U-234	F	2.00E-02	1	0.3	0.27
U-234	F	2.00E-02	5	0.25	0.23
U-234	F	2.00E-02	10	0.18	0.17
U-234	M	4.00E-03	0.3	3.1	0.21
U-234	M	4.00E-03	1	2.2	0.15
U-234	M	4.00E-03	5	1.4	0.086
U-234	M	4.00E-03	10	0.85	0.045
U-234	S	2.00E-04	0.3	30	0.054
U-234	S	2.00E-04	1	23	0.039
U-234	S	2.00E-04	5	13	0.021
U-234	S	2.00E-04	10	7.2	0.0097
U-234	F/M	1.60E-02	0.3	0.93	0.28
U-234	F/M	1.60E-02	1	0.64	0.2
U-234	F/M	1.60E-02	5	0.41	0.12
U-234	F/M	1.60E-02	10	0.24	0.071
U-234	M/S	6.00E-04	0.3	11	0.1
U-234	M/S	6.00E-04	1	8.5	0.074
U-234	M/S	6.00E-04	5	5.5	0.039
U-234	M/S	6.00E-04	10	3.4	0.018
U-234		2.00E-03	0.3	6.2	0.14

U-234		2.00E-03	1	4.6	0.098
U-234		2.00E-03	5	3	0.051
U-234		2.00E-03	10	1.8	0.024
U-235	F	2.00E-02	0.3	0.33	0.29
U-235	F	2.00E-02	1	0.27	0.25
U-235	F	2.00E-02	5	0.23	0.21
U-235	F	2.00E-02	10	0.17	0.16
U-235	M	4.00E-03	0.3	2.8	0.19
U-235	M	4.00E-03	1	2	0.14
U-235	M	4.00E-03	5	1.3	0.08
U-235	M	4.00E-03	10	0.78	0.042
U-235	S	2.00E-04	0.3	28	0.052
U-235	S	2.00E-04	1	21	0.037
U-235	S	2.00E-04	5	12	0.02
U-235	S	2.00E-04	10	6.6	0.0093
U-235	F/M	1.60E-02	0.3	0.86	0.26
U-235	F/M	1.60E-02	1	0.58	0.19
U-235	F/M	1.60E-02	5	0.38	0.12
U-235	F/M	1.60E-02	10	0.22	0.066
U-235	M/S	6.00E-04	0.3	10	0.096
U-235	M/S	6.00E-04	1	7.8	0.07
U-235	M/S	6.00E-04	5	5.1	0.036
U-235	M/S	6.00E-04	10	3.1	0.017
U-235		2.00E-03	0.3	5.7	0.13
U-235		2.00E-03	1	4.2	0.091
U-235		2.00E-03	5	2.8	0.048
U-235		2.00E-03	10	1.7	0.023
U-238	F	2.00E-02	0.3	0.31	0.28
U-238	F	2.00E-02	1	0.26	0.24
U-238	F	2.00E-02	5	0.22	0.2
U-238	F	2.00E-02	10	0.16	0.15
U-238	M	4.00E-03	0.3	2.7	0.18
U-238	M	4.00E-03	1	1.9	0.13
U-238	M	4.00E-03	5	1.2	0.076
U-238	M	4.00E-03	10	0.73	0.04
U-238	S	2.00E-04	0.3	27	0.048
U-238	S	2.00E-04	1	20	0.035
U-238	S	2.00E-04	5	12	0.018
U-238	S	2.00E-04	10	6.3	0.0086
U-238	F/M	1.60E-02	0.3	0.82	0.24
U-238	F/M	1.60E-02	1	0.55	0.18
U-238	F/M	1.60E-02	5	0.36	0.11
U-238	F/M	1.60E-02	10	0.21	0.062
U-238	M/S	6.00E-04	0.3	9.8	0.091
U-238	M/S	6.00E-04	1	7.4	0.066

U-238	M/S	6.00E-04	5	4.8	0.034
U-238	M/S	6.00E-04	10	2.9	0.016
U-238		2.00E-03	0.3	5.4	0.12
U-238		2.00E-03	1	4	0.086
U-238		2.00E-03	5	2.6	0.045
U-238		2.00E-03	10	1.6	0.021

TABLE 12-6: INGESTION DOSE COEFFICIENTS (ICRP 137)

		fA-	e(50)
	Chem. Compounds		µSv/Bq
Pb-210	All	2.00E-01	0.320
Pb-212	All	2.00E-01	0.006
Bi-212	All	5.00E-02	0.000
Bi-214	All	5.00E-02	0.000
Po-210	All	1.00E-01	0.180
Ra-223	All	2.00E-01	0.041
Ra-224	All	2.00E-01	0.029
Ra-226	All	2.00E-01	0.130
Ra-228	All	2.00E-01	0.340
Ac-227	All	5.00E-04	0.170
Th-227	All	5.00E-04	0.001
Th-228	All	5.00E-04	0.031
Th-230	All	5.00E-04	0.060
Th-232	All	5.00E-04	0.070
Pa-231	All	5.00E-04	0.180
U-234	Soluble	2.00E-02	0.034
U-234	Insoluble		
U-235	Soluble	2.00E-02	0.032
U-235	Insoluble	2.00E-03	0.003
U-238	Soluble	2.00E-02	0.031
U-238	Insoluble	2.00E-03	

TABLE 12-7: DOSE CONVERSION COEFFICIENT, AMBIENT DOSE EQUIVALENT H*(10) TO EFFECTIVE DOSE E FOR CHILDREN OR OTHER RADIATION FIELDS

TABLE 12-8: RELATIONS BETWEEN WL/WLM AND THE SI-UNITS

TABLE 12-9: DATA ON RADON EMANATION AND EXHALATION RATE OF NORM REUSED IN EUROPEAN COUNTRIES

Numbers in Bold Italic= MDA (minimum detection level)

<u>Numbers in Bold underline= average from minimum and maximum</u>

NORM	N.	d	Density	Emanation	Exhalation rate		^{226}Ra	Ref.
		(cm)	(kg m^{-3})	(%)	value	unit	(Bq kg^{-1})	
By-products Gypsum								
Phosphogypsum board	22			14	1548	mBq m^{-2} h^{-1}	430 (330-520)	BE2
By-product gypsum	1	6.7			13900	mBq m^{-2}h^{-1}	319	FIN2
By-product gypsum	1							FIN2
		20			42300	mBq m^{-2}h^{-1}	482	FIN2
		15			31200	mBq m^{-2}h^{-1}	482	FIN2
		10			20300	mBq m^{-2}h^{-1}	482	FIN2
		7.5			18600	mBq m^{-2}h^{-1}	482	FIN2
		5			10100	mBq m^{-2}h^{-1}	482	FIN2
		2.5			4700	mBq m^{-2}h^{-1}	482	FIN2
Phosphogypsum	1	7	960	18	4800	mBq m^{-2}h^{-1}	103	NL4
Phosphogypsum	1	7	960	19	15800	mBq m^{-2}h^{-1}	330	NL4
Phosphogypsum	1	1	840	13	2500	mBq m^{-2}h^{-1}	700	NL4
Phosphogypsum	1	7	900	3	200	mBq m^{-2}h^{-1}	26	NL4
Chemical gypsum (board)	3	7		7	9.6	Bq m^{-2}h^{-1}	450 (320-700)	NL3
By product gypsum	4							PL4
		9		4			26	
		9		13			699	
		9		21			736	
		9		20			585	
Phosphogypsum	7				18.2 (4-74.2)	Bq m^{-2}h^{-1}	166 (12-705)	POR1
Ashes								
Coal ash	15			0.5	5	mBq kg^{-1} h^{-1}	140 (120-180)	DK2
Coal ash	16			0.4	49	mBq kg^{-1} h^{-1}	170 (130-200)	DK2
Coal ash	14			0.4	49	mBq kg^{-1} h^{-1}	160 (130-190)	DK2
Coal ash	12			0.9	10	mBq kg^{-1} h^{-1}	150 (120-170)	DK2
Fly ash	9			2 (0.06-11)				
Fly ash	12				176 (43-421)	mBq kg^{-1}h^{-1}	929 (663-1176)	GR8
Bottom Ash	2				176 (133-220)	mBq kg^{-1}h^{-1}	61 (580-654)	GR8
Fly Ash (USA)	10			2	23	mBq kg^{-1} h^{-1}	170	IT2
Fly Ash (Sud Africa)	19			1	16	mBq kg^{-1} h^{-1}	170	IT2
Bottom Ash	5			3	24	mBq kg^{-1} h^{-1}	130	IT2
Fly ash	4			0.5-1.5			174 (126-222)	NW3
Fly ash	33			0.5(0.2-1.2)			96 (63-144)	PL4
Metallurgical Slags								
Slag	11	9		0.7 (0.2-1.5)			67 (37-144)	PL4
Slag	3			0.4 (0.3-0.4)				
Slagstone	1		1930	2	648	mBq m^{-2}h^{-1}	78	GE2

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