Environment International 175 (2023) 107954

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Full length article

Tools for harmonized data collection at exposure situations with naturally occurring radioactive materials (NORM)

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A R T I C L E I N F O

Handling Editor: Olga Kalantzi

Keywords:
NORM
Registers
Uranium
Thorium
NORM involving industry
exposure doses associate with NORM
Radiation protection

A B S T R A C T

Naturally occurring radioactive materials (NORM) contribute to the dose arising from radiation exposure for workers, public and non-human biota in different working and environmental conditions. Within the EURATOM Horizon 2020 RadoNorm project, work is ongoing to identify NORM exposure situations and scenarios in European countries and to collect qualitative and quantitative data of relevance for radiation protection. The data obtained will contribute to improved understanding of the extent of activities involving NORM, radionuclide behaviours and the associated radiation exposure, and will provide an insight into related scientific, practical and regulatory challenges.

The development of a tiered methodology for identification of NORM exposure situations and complementary tools to support uniform data collection were the first activities in the mentioned project NORM work. While NORM identification methodology is given in Michalik et al., 2023, in this paper, the main details of tools for NORM data collection are presented and they are made publicly available.

The tools are a series of NORM registers in Microsoft Excel form, that have been comprehensively designed to help (a) identify the main NORM issues of radiation protection concern at given exposure situations, (b) gain an overview of materials involved (i.e., raw materials, products, by-products, residues, effluents), c) collect qualitative and quantitative data on NORM, and (d) characterise multiple hazards exposure scenarios and make further steps towards development of an integrated risk and exposure dose assessment for workers, public and non-human biota.

Furthermore, the NORM registers ensure standardised and unified characterisation of NORM situations in a manner that supports and complements the effective management and regulatory control of NORM processes, products and wastes, and related exposures to natural radiation worldwide.

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https://doi.org/10.1016/j.envint.2023.107954
Received 23 January 2023; Received in revised form 21 April 2023; Accepted 25 April 2023
Available online 11 May 2023
0160-4120/

1. Introduction

Naturally occurring radioactive material (NORM) is defined as radioactive material containing no significant amounts of radionuclides other than naturally occurring radionuclides (NOR), *i.e.*, the primordial radionuclides ^{40}K, ^{235}U, ^{238}U and ^{232}Th and their radioactive decay products. Materials in which activity concentrations of NOR have been changed by a process (i.e., due to human activity) is included under term NORM (IAEA Safety Glossary, 2022). Commonly, NOR is present in the environment in a wide range of activity concentrations (UNSCEAR, 2008) and it is important to have good knowledge of these radionuclides in different exposure scenarios since many are long-lived and have a high radiotoxicity that may significantly affect workers, the public or the environment, under different conditions (ICRP, 2019; Michalik, 2009; Mrdakovic Popic et al., 2011).

Naturally elevated ^{232}Th and ^{238}U levels can occur in some areas, leading to higher than average radiation exposure doses to people and non-human biota (NHB); these sites are known as '*high background natural radiation areas*' (HBRA) (Ghiassi-Nejad et al., 2002; Paschoa, 2000; Wei and Sugahara, 2000; UNSCEAR, 2008). Moreover, natural resources containing NOR are used in many industries where processes may enhance activity concentrations in products and residues, including bulk residues, slags, scales, waste and discharges of liquid, vapour and dust. These industrial processes and associated materials need to be considered from a radiation protection point of view due to the risk of potential exposures of workers, members of the public, and NHB in the affected environment (ICRP, 2019). There are also historic sites of NORM mining and processing, resulting in NORM affected legacy sites at which radiation protection and environmental safety requirements were seldom considered, or were not applied to current standards. Many such sites are old, of unknown ownership, and are contaminated with NORM residues and waste as well as additional mixed hazards. Example sites include old mines and deposits associated with radionuclides and heavy metals leaching and exhalation of radon and thoron (Mrdakovic Popic et al., 2011; Pereira et al., 2014; Sneve et al., 2020).

Although historically neglected in comparison to the artificial radionuclides, international work on NORM, regarding both research and regulatory aspects, has been somewhat intensified during the last decades (*e.g.*, EC, 1999; a series of International NORM symposia, 1997-2022, IAEA MODARIA Programme I and II, 2015, 2019; IAEA, 2018; RadoNorm project, 2020-2025; TERRITORIES project-EJP CONCERT, 2017–2020). This work has progressed in parallel with the development and implementation of regulatory requirements for radiation protection (EC, 1996; EC, 2014; IAEA, 2014, IAEA, 2021). As recent illustrative example, one of the driving forces behind the currently increased international work on NORM is change of exemption and clearance levels for certain NOR in European countries after the implementation of European Council Directive 2013/59/Euratom (EU BSS) (EC, 2014).

However, knowledge gaps and uncertainties still exist, particularly with respect to the number and extent of NORM sites, details of exposure situations that include NOR behaviour, mobility and transportation, possible contamination, exposure doses and effects they can cause in different conditions. These issues have been acknowledged in peer review articles worldwide, strategic agendas for future radiation protection research and in regulatory documents (*e.g.*, Al Nabhani et al., 2016; Gilbin et al., 2021; HERCA, 2021; ICRP, 2019; Michalik, 2009; Michalik et al., 2013; Turcanu et al., 2022; UK, 2014). Moreover, requirements in the EU BSS, regarding NORM involving practices, need to be tackled by both industry operators and regulators, while simultaneously the radiological impact from industries involving NORM is a growing concern to stakeholders (Turcanu et al., 2022).

Many countries have various types of NORM exposure situations that need to be identified and categorised in a standardised way, to ensure such records can be kept in a general NORM inventory with consideration of all relevant by-products, discharges of liquids and gases as well as the generation of residues and waste in order to facilitate proper radiation protection. Moreover, to be able to internationally compare and exchange best available practices regarding regulation and management of NORM it is important to obtain a panoramic overview of NORM exposure situations. This overview, which may be the outcome of an iterative data collection process, needs to capture radiation risk and other relevant factors with necessary information on their characteristics, management options and level of graded approaches needed for regulatory control.

Examples of the existing national NORM inventories include available reports and papers on NORM involving industries and waste from different countries, e.g., Germany (Gellermann et al., 2001; Hummrich et al., 2010; Gellermann et al., 2018), Ireland (Organo and Fenton, 2008) and the Netherlands (Folkertsma and van der Schaaf, 2017; Huijbregts et al., 2000). Furthermore, available worldwide literature presents different case studies on particular issues of radiological concern related to industrial processes involving NORM (*e.g.*, Barros et al., 2018; Dewar et al., 2014; Flues et al., 2002; Kunze et al., 2019; Mantero et al., 2013). However, based on the results obtained by the RadoNorm project survey on NORM, conducted in 2022 (*unpublished data)* as well as an expert literature review, a precise, step-by step, internationally adopted methodology for making NORM inventory and effective tools for a systematic and harmonized data collection have has been missing in many European and worldwide countries. The existing national inventory and industry specific publications are mostly of limited general use for all NORM situations as they are commonly written in different national languages or focused to specific NORM involving activities, issues or specific fields. As noted above, research data gaps related to NOR behaviour and risk assessment still exist concerning particular NORM exposure situations and specific NORM issues (Chen, 2022; Joyce et al., 2017; Koppel et al., 2021; Michalik, 2009; Al Nabhani et al., 2016). Therefore, the focus of an international expert group within the European RadoNorm project (www.radonorm.eu) was to improve knowledge and understanding of various aspects of NORM.

The main objective for development of NORM registers was related to the RadoNorm project as it was foreseen that their use should facilitate an ongoing comprehensive collection of qualitative and quantitative data from NORM sites across Europe, in a systematised and harmonised way, by the RadoNorm researchers. Using such tools, data will be collected that includes as many as possible relevant details. The overall gathered data will then allow making an updated European overview of NORM exposure sites that will represent a step forward to extend the international database for information on NORM, with relevant data of comparable quality. Moreover, the collected data are expected to significantly improve characterisation of the NORM sites and scenarios with respect to NOR behaviour, accumulation or mobilisation in different conditions, exposure pathways, exposure doses for workers, public and non-human biota. Considering these aspects, these NORM registers are intended to be used primarily by researchers worldwide conducting different research and investigation based on big, harmonised datasets.

An additional and equally important objective of NORM registers is in line with the general RadoNorm project objective to directly translate outcomes of the research and investigation into sound, feasible and applicable improvements, which will support countries in implementation of EU BSS, or wider IAEA BSS. Clearly, these available registers will not be solely for research but will also support regulatory issues identified by regulators and NORM industry operators, in NORM inventory processes in countries that need initial or periodical, updated review of NORM inventory but do not have available and clear methodology and tools. With NORM registers, storing, retrieving, and easy managing data will be ensured.

Therefore, the main objective of this paper is to make publicly available and present the series of NORM registers developed for extraction of information and data collection for different NORM exposure situations, by evaluation of their main features and the assumptions used in development process.

2. Categories of NORM exposure situations

To decide on NORM exposure situations for which specific NORM registers need to be developed, two activities within the RadoNorm project were conducted in 2021 and 2022:

- an international exercise among project participants (14 countries) to collect basic information on presence of active or inactive (potential legacy) NORM involving industries and HBRA sites, and,
- an international NORM survey, with a comprehensive set of NORM related questions of relevance for research, management and regulation, which was submitted to all European countries, but also wider to countries worldwide.

Based on pooled results, obtained from 27 countries that participated either in the RadoNorm exercise or in the NORM survey or in both, a list of the most abundant NORM involving industrial activities and other sites (HBRA and legacy), subject of the current study, was made as follows:

1. High Background natural Radiation Areas (HBRA),
2. Oil and gas production,
3. Geothermal energy production,
4. Phosphate fertiliser production,
5a. Zircon industry, tiles,
5b. Zircon industry, refractories,
6. Cement production,
7. Phosphoric acid production,
8. TiO_2 production,
9. Primary iron production,
10. Non-ferrous metals smelting,
11. Coal fired power plants,
12. Ground water filtration facilities,
13. Mining industry (including Coal mining),
14. Legacy sites (NORM affected), and
15. Other NORM involving activity, a generic register.

As a key objective was to provide an efficient and user-friendly register for most relevant NORM exposure situations, specific NORM registers were developed for each of the above given NORM exposure situations, found to be present in more than 50 % of the investigated European countries.

Concerning the NORM involving industry only, the developed NORM registers cover 12 separate industrial activities, out of the 16 given in the 'Indicative list' of EU BSS (EC, 2014). However, an additional generic register named "*Other NORM involving activity*", to be used for any other activity that could be identified in any country, was also developed to ensure that other activities from the indicative lists of the EU BSS, IAEA BSS but also potential, additional ones outside the indicative lists, such as potash mining, aluminium bauxite production, pulp and paper mills, other than mining underground workplaces, *et cetera,* may also be included.

3. Developed NORM registers for systematic information and data collection

In this section, after the explanation of methodology for identification of NORM sites and intended application of NORM registers, the structure of the registers and the main topics addressed for information and data collection are detailed.

3.1. NORM identification and application of NORM registers at identified exposure situations

Prior to data collection, it is necessary to identify NORM exposure sites if these are unknown in a country. A systematic, tiered approach has been developed to identify all situations when exposure to NOR cannot be neglected from a radiation protection perspective considering NOR characteristics and potential changes to NOR content in the various industrial processes (Michalik et al., 2023). The methodology assumes an initial position of limited knowledge of the situation and proposes several tiers:

a) analysis of the presence of natural mineral resources,
b) identification of ongoing and any former mining industries,
c) Identification of ongoing and former mineral/fossil fuels processing industries, and
d) analysis of commodities and products life cycle, including their application and final disposal.

Once a NORM exposure situation has been identified, the developed registers ensure complete qualitative and quantitative characterisation by a set of questions adapted to the exposure situation of concern. In case of industrial activities involving NORM, characterisation is ensured through a structured process of consideration of the production process starting with the raw materials, the main products and technological processes (where relevant), the generation of residues and waste at facility site, followed by consideration of releases to soil, air and water of the surrounding environment, as shown in Fig. 1. This technique, being adapted to different possible situations and with respect to different materials and NORs, ensures collection of relevant data for researchers' work on exposure scenarios, transport pathways and related doses and risk. Additionally, the application of registers (in whole or partially) may contribute to improvement of the ability of site operators and regulators to identify potential NORM, to facilitate regulatory control, and also to increase awareness about possible exposures.

Having country specific knowledge in the development process of the tools and methodology for their application was important since differences in approaches to identifying NORM cases as well as extracting data from these among European countries, is linked to both how the EU BSS (1996, 2013) have been interpreted and implemented, and also to previously existing national regulatory initiatives concerning NORM, each country's infrastructure, awareness of NORM industries, how exposure scenarios are characterised in each country.

Application of NORM registers, by using a comprehensive set of different qualitative and quantitative questions, is advised for the RadoNorm participants in order to help (a) identify the main features and parameters for characterisation of a NORM site or activity, (b) gain an overview of all materials involved such as raw materials, products, by-products, residues, effluents, discharges, (c) collect qualitative and quantitative information on NOR, and (d) characterize multiple hazards exposure scenarios to obtain data that will allow further research and investigation and contribute to development of an integrated impact and risk assessment for workers, public and NHB.

However, when applied for regulatory purposes for compiling a NORM inventory by regulators and industry operators, a graded approach that includes iterative process is advised in application of NORM registers. This can be achieved by starting with a simple conservative assessment that is a screening stage with making use of generic input data, under the assumption of cautious exposure scenario. Then, if needed, increasing the complexity and realism of the assessment as necessary, which can be done by using more detailed questions in registers concerning data for realistic exposure scenarios. In this iterative process, the close collaboration of regulators, who should provide the advice and information on required screening and characterisation steps, and industry operators, who should provide the operational data to reply to the regulators requests, is facilitated when use NORM registers.

Target groups of end-users for NORM registers include:

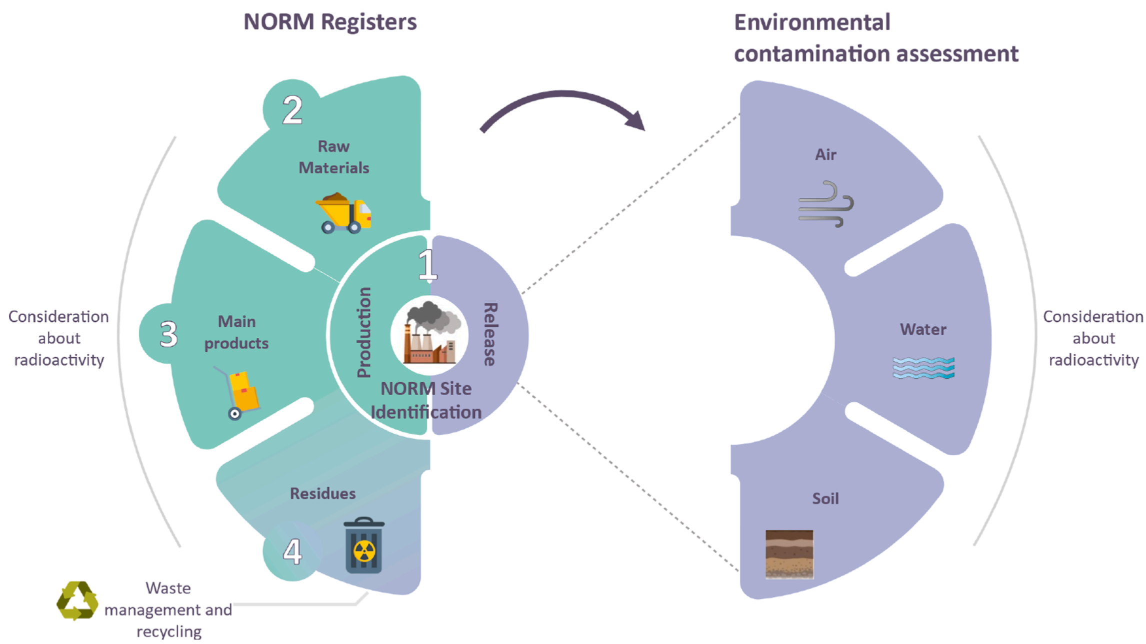

Fig. 1. Data collation flow process by NORM registers at identified NORM involving industries.

- International researchers (in the RadoNorm project and wider) that may collect comprehensive data sets from different NORM exposure sites in order to explore various issues,
- Regulators that may use registers for conducting NORM inventories, especially in national situations worldwide where initial inventory is necessary/planned, while neither a precise methodology nor tools for NORM inventory are available. Moreover, NORM registers are foreseen to be useful for characterisation and decision-making concerning process of remediation at NORM-affected legacy sites,
- Industry operators that may use registers for an initial screening or a systematic radiological characterisation and impact assessment of their sites, and,
- Academics and international experts doing training courses on NORM inventory, exposure characterisation, but also teaching about specific industrial activities involving NORM and radiation protection issues.

3.2. Structure of NORM registers

For each of the NORM involving industry categories listed in Section 2, a register was developed in the form of a spreadsheet software (*Microsoft Excel* workbook[1]).

NORM registers are made with a level of flexibility as they are intended to be used as generic tools for collecting available general information and data on specific industrial sector or NORM exposure category identified on the level of a country, but also as site specific tools where data from a specific facility can be gathered, when available.

Each register contains three parts: 1) descriptive data, 2) quantitative data, and 3) predefined information to support characterisation of technological or other processes of concern.

- Descriptive data
  - o A sheet named *"Category of Industry-General"* with general questions concerning:
    - ■ Number of particular NORM situations and facilities in the country,
    - ■ Legislative aspects in the country regarding exemption and clearance levels (for solid material, liquid and gaseous wastes and discharges),
    - ■ Application of a graded approach for regulatory control,
    - ■ Identification of regulatory and scientific challenges, and any other remarks.
  - o One or more sheets named *"Category of Industry-Industry #"* with a set of questions related to an individual facility or a group of NORM facilities. Questions in this sheet are divided in the groups:
    - ■ *Site(s) description*, containing general questions on description of the occurrence of NORM in a specific facility or group of facilities and the total number of exposed workers,
    - ■ *Other relevant considerations about radioactivity and other hazards,* with questions in the following subgroups:
      - Monitoring programs and other hazards, including questions on the accumulation, mobility and transport of radionuclides, and the presence of other non-radioactive hazards as well as implemented occupational, health, safety and environmental protective measures,
      - Dose assessment for workers, public and non-human biota,
      - Regulatory control at individual facility.
- Quantitative data
  - o *Quantitative information*, containing questions on various NORM categories (raw materials, main products, residues, liquid effluents, atmospheric discharges) aimed a more detailed characterisation and quantification of potential NORM with which the industries are dealing with, and of its processing operations, namely on:
    - ■ Type of materials present,
    - ■ Annual quantity of material of concern,
    - ■ Destination and treatment,
    - ■ Activity concentration results (range, mean and median values) of different measured radionuclides (^{238}U, ^{232}Th, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{210}Pb, ^{210}Po, ^{40}K for all NORM registers, and ^{220}Rn, ^{222}Rn, PAEC ^{220}Rn, ^{222}Rn, total alpha,

[1] More information is available in the supplementary material for this paper.

total beta for certain NORM registers where these NOR can be of relevance).

- Predefined information
    - o An Excel sheet *'Drop down Menu'* containing a list of possible answers (multiple choice options) for closed questions in the previous Excel sheets. An important characteristic of this part is the provision of a predefined list of possible materials associated with the different technological processes of concern. In addition, for each closed question, the possibility is provided to respondents to add (their) specific answers (e.g., when the answer they would like to provide is missing from the pre-defined drop-down menu of answers). New materials and different ones from those already included as possible answers can be added and then selected by end-users so that all situations can be completely described.

All the independent parts of the Excel workbook are colour coded to facilitate the process of recording data. To facilitate the future analysis of answers, closed questions were used whenever possible, using questions having a fixed list of possible answers (for example, see Fig. 2). A user manual complements the registers and facilitates their completion.

3.3. Main topics addressed by NORM registers

The type of information and data to include in the registers, to support radiation protection of workers, public and environment, following the identification of NORM industries and exposure situations by means of the developed tiered methodology (Michalik et al., 2023), were chosen as a result of a comprehensive international joint literature review (*e.g.* EC, 2014; IAEA, 2014; ICRP, 2019) and expert discussions.

It emerged that, for any given NORM involving industry or situation, it is important to obtain information about the following main issues:

1. Legislative aspects of NORM management and regulatory approaches in the country,
2. Occurrence of NOR in different materials in industries and existing exposure situations,
3. NOR mobility and transport in the environment, monitoring programmes,
4. Presence of non-radioactive hazards,
5. Dose assessment for workers, public and non-human biota,
6. Activity concentration of relevant radionuclides (^{238}U and ^{232}Th and respective progeny and considering possible disequilibria in the series, ^{40}K) in different material categories, and,
7. Destination and treatment of NORM residues and wastes.

In the following sub-sections, the importance of each of these topics for the registers, along with the categorisations used for data collection, are discussed.

3.3.1. Legislative aspects of NORM and regulatory approaches in the country

Council Directive 2013/59/Euratom (EU BSS) requires the management of NORM involving activities within the same regulatory framework as other practices involving radioactivity. European countries have implemented the requirements within their national legislation in the different ways since the Directive provides certain degree of flexibility. This is particularly true for the application of exemption and clearance concepts (see Annex VII of EU BSS), which are among the mechanisms for establishing a graded regulatory approach commensurate with the potential radiation exposure risks. In fact, it has been recently identified that most European Member States have adopted the exemption and clearance levels and a dose constraint provided by the latest EU BSS, but that somewhat different national approaches for NORM regulatory control and radiation protection have been established (HERCA, 2021). For example, some countries adopted a dose criterion lower than 1 mSv y^{-1} (applied in addition to the natural radiation background) for the exemption of NORM waste disposal from regulatory control or for recovery of certain NORM residues. Similarly, different approaches have been adopted for control of gaseous discharge and liquid effluents. It has been emphasised that these differences need further consideration at international levels (HERCA, 2021). Therefore, to enable further exchange and work on these issues, questions have been included in the NORM registers on the following:

- *Graded approach for exposure control within the country, including waste disposal and recovery,*
- *Exemption and Clearance levels,*
- *Regulatory challenges identified.*

3.3.2. Occurrence of NOR in different materials in industries and existing exposure situations

When considering radiation protection from NORM, it is of high importance to identify where enhanced NOR activity concentrations occur. In industries, this may include accumulation of certain NOR during the technological processes, such as well-known NOR accumulation in scales within the pipelines in oil and gas industry. In the

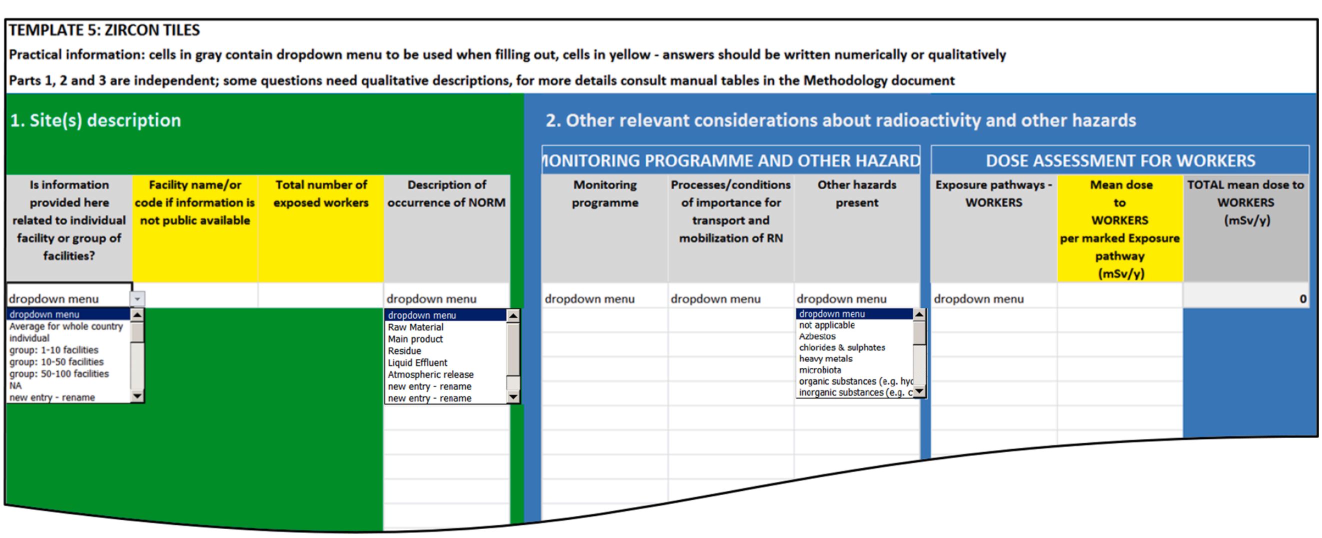

Fig. 2. Illustration of the zircon tiles industry register (extraction from related Excel sheet).

environment, NOR concentrations may be enhanced depending commonly on complex environmental conditions, such as case of acidic leaching of NOR from excavated alum shale rocks, in changeable redox conditions, with presence of other ions that influence radionuclide speciation and thus their mobility and final fate.

In particular, the following material categories have been considered with respect to NOR occurrence for industrial activities:

- Raw material and additional materials (*e.g.*, fuel, chemical reagents),
- Main products and by-products,
- Residues and waste,
- Liquid effluents, and
- Atmospheric releases.

Knowledge of activity concentrations of NOR and understanding of their distribution in different industrial processes and waste management processes, as well as in different ecosystems of concern post to their release is important for developing proper radiation protection control mechanisms. Such mechanisms should be acceptable to all involved parties and be transparent and understandable to members of the public and involved stakeholders (Cinelli et al., 2020; Mrdakovic Popic et al., 2011; Sneve et al., 2020; Turcanu et al., 2022).

In the series of developed registers, a predefined list of most common materials†, under each given material category, including raw material, main product, residues, effluent, *et cetera,* within an industrial process, is provided. Questions on the occurrence of NORM in all material categories are included. To account for the different and numerous NORM involving activities, specific but most commonly present materials are provided for each NORM industrial activity (Table 1). As emphasised above, the possibility to add different materials is also provided to end-users. Similar approach was adopted for HBRA exposure site.

For legacy sites, main information requested by NORM register is

Table 1
Categorisations used for NORM occurrence in some of the registers available for industrial activities involving NORM†.

NORM activity	Raw materials	Main product	Residues	Liquid effluent	Atmospheric release
Oil and gas production	Drill solids Fracturing fluid New entry …	Oil Gas	Scales Sludge Drilling mud Contaminated scrap from gas exploitation	Formation water New entry ….	Natural gas-film (black powder, different forms) Natural gas – dust from filtering system …..
Geothermal energy production	Geothermal fluid		Scales Sludge Filter material Precipitates	Aqueous discharge New entry ….	Dust emission Vapour emission New entry ….
Phosphate fertilisers and phosphoric acid production	Phosphate rock Sedimentary phosphate rock Igneous phosphate rock Phosphoric acid Mixed raw materials New entry …..	Phosphate fertiliser Polyphosphates as food additives Beverages Animal feed New entry …	Phosphogypsum Scales Sludge New entry …..	Liquid effluents New entry ….	Dust emission Vapour emission New entry ….
Zircon industry -tiles - refractories	Baddeleyite (zirconia, ZrO_2) Zircon sands (*Country of origin*) Clay …	Tile (glazed single or double fired) Porcelain stoneware Refractory Zirconia mullite …	Hydrated lime General air exhauster dust Fusion furnace dust Sludge …	Liquid effluents New entry ….	Dust emission Vapour emission New entry ….
Cement production	Limestone Clay Ferrous slag Sand …	Clinker Portland cement (CEM I) Pozzolanic cement (CEM IV) Supersulfated cement (SSC) …	Clinker scale in oven Smoke abatement dust Scales from chimney Sludge	Liquid effluents New entry ….	Dust emissions Vapour emission New entry ….
Coal fired power plants	Brown coal – lignite Black lignite (sub-bituminous) Coke Low sulphur coal …..		Bottom ash Fly ash Boiler slag Fluidised Bed Combustion Gypsum	Liquid effluents New entry ….	Dust emissions Vapour emission New entry ….
Ground water filtration facilities	Raw groundwater	Drinking water	Sand filter Anthracite filter Limestone filter Activated carbon filter ….	Backwash of sand filter Backwash of anthracite filter Backwash of limestone filter Discharge from sludge settling pond …….	Dust emission Vapour emission New entry ….
Mining industry	Ores (to specify) Minerals (to specify) New entry ….		Solid waste - rocks Solid waste – soil Solid waste – mixed Sludge ….	Liquid effluents New entry ….	Dust emission Gas emission New entry ….

regarding the characterisation of the present contaminants, what is expected to further provide a site-specific basis for consideration of remediation options and a final decision-making. No well-defined categorisation was adopted regarding various raw materials used in the past, as these often are unknown and represent only one component of importance for legacy site characterisation prior to remediation. Instead, characterisation starts with main description of identified legacy site and information where elevated NOR occur at such exposure situation. Examples of possible answers include decommissioned facilities or installations contaminated with NORM, old NORM waste present at active site, soil or land contaminated with NORM from various historic activities, water bodies contaminated with NORM, NORM accumulated in biota due to the previous human activities, *et cetera*.

Notably, the following information in Table 1. contains only a subset of all the items included in the registers †.

Information regarding radionuclides activity concentrations of the materials selected from the previous tables are requested, where available, as described in 3.2.

3.3.3. NOR mobility and transport in the environment, monitoring programmes

Understanding the mobility and/or accumulation of radionuclides is of prime importance in risk assessments for workers, public and the environment. In minerals and rocks, in undisturbed natural conditions, radionuclide progeny within the ^{238}U and ^{232}Th decay series are in secular equilibrium with the parent radionuclides, although disequilibrium may arise from the outgassing of ^{222}Rn, and to a lesser extent ^{220}Rn, through cracks in the rocks (Sheppard et al., 2006). However, for industrial activities that involve raw materials classified as NORM, the situation can be more complex. The radionuclides constituting these decay series include isotopes of 10 different elements and the secular equilibrium, commonly assumed in raw materials, may be disturbed by a variety of processes and conditions in different industries and environments (EC, 1999; 2002; Guo et al., 2007; Michalik et al., 2013; Mrdakovic Popic et al., 2014; Smith et al., 2004; Vandenhove et al., 2007). When exposed to these different processes and conditions, the elements can behave differently in terms of accumulation, mobility and transport, eventually leading to disequilibrium or formation of a subseries. Therefore, understanding the physical and chemical conditions in each process of concern, including the possibility of accumulation and migration of radionuclides from the production site to the environment, is essential for the proper evaluation of a situation. An illustrative example is a formation of material with enhanced NOR concentrations when processing minerals and raw materials in different industrial processes that happens at high temperatures (*e.g.* iron and steel production). An enhanced ^{210}Pb and ^{210}Po activity concentration, found in dust, residues, sludge and scale may be of concern as these radionuclides can give radiation exposure dose to workers and members of public due to possible inhalation (Długosz-Lisiecka, 2016; Khater and Bakr, 2011; Li et al., 2018).

Another example illustrating the different behaviour of NOR within NORM involving industries is the exploitation processes in the oil and gas industry. Commonly, the parent radionuclides ^{238}U and ^{232}Th are not mobilised from the reservoir rocks and are not found in the oil, gas or formation water. However, formation water contains ^{226}Ra that is, together with other similar elements, such as calcium, strontium, and barium, in dissolved or finely dispersed form. When discharged from the facility in these forms, ^{226}Ra may lead to environmental contamination through different processes of mobilization, transportation, and incorporation into food chains (Eriksen et al., 2006; Veguería et al., 2002). Additionally, formation water contains ^{228}Ra and ^{224}Ra from the ^{232}Th series. Changes in temperature and pressure in formation water can lead to precipitation of mixed products of sulphate and carbonate scales on the inner walls of production equipment, including tubing, valves, pumps, offshore pipelines *et cetera* (Garner et al., 2015; Koppel et al., 2021). Another NOR of concern is ^{210}Pb that may occur as unsupported and supported ^{210}Pb; in either case, the decay of ^{210}Pb leads to the production of the highly radiotoxic, and potentially volatile alpha emitter, ^{210}Po. Deposits containing unsupported ^{210}Pb are associated with dispersed particles and colloids, mainly deposited on the inside surfaces of pipes, in form of a very thin and stable deposit, in equipment that has been in contact with the produced water in such a way that, over time, ^{210}Pb may be converted into other compounds, depending on prevailing conditions in the system. The supported ^{210}Pb forms due to additional mobilisation of radionuclide ^{222}Rn that is associated with the stream of oil, gas and water. Radon, as highly mobile gas, travels with the gas–water stream long distances through the pipeline before decaying and forming a deposit. Its decay progeny, ^{210}Pb is, thus, deposited at different locations, at internal surfaces of pipes and other equipment in gas processing plants in the form of thin layers (Faria and Moreira, 2018; IAEA, 2003).

Understanding the physical and chemical processes that influence the accumulation of contaminants within the production site, is essential for estimation and mitigating of potential radiation exposure. When features of technological processes and important parameters are known, the prediction of radionuclide behaviour, and consequently occupational and public radiation exposure dose, in each situation will be enabled. However, it is more complex when NOR occur, due to human activities, in enhanced concentration in the environment, and when further transported and mobilised in different environmental compartments depending on prevailing environmental conditions. The most important transportation processes are included in the categorisation of the developed registers to provide updated and new information of relevance for characterisation of environmental exposure and estimation of exposure doses to public and non-human biota (Table 2).

3.3.4. Presence of non-radioactive hazards

Industrial activities involving NORM and the presence of NORM-affected legacy sites commonly give rise to multiple hazards for which the radiological hazard is not necessarily the dominant one. Consequently, there are research, management, and regulatory aspects of importance at these multiple-hazards exposure sites for further consideration.

While presence of multiple hazards at NORM exposure sites is well-known (ICRP, 2019), studies on exposure characterisations and integrated risk assessment that include NOR and other hazards have still been limited and mainly in laboratory conditions (Beaumelle et al., 2016; Bréchignac and Desmet, 2005; Salbu et al., 2019; Thompson et al., 2005; Xiong and Wang, 2021). To make an improvement, the multiple hazards concept should be developed focusing on the multiple source term, ecosystem exposure and possible interactions, biological uptake and effects as an overall basis for assessing impact and risk from simultaneously present hazards including NOR (Salbu et al., 2019).

On the regulatory side, international organisations strongly suggest applying an inclusive, graded operative and regulatory approach for radiation protection, in which the radioactive hazards coming from NORM are considered, assessed and integrated alongside the non-radioactive hazards (NRH) that may include chemical pollutants, biological and physical hazards or even other things that may present constraint in certain ways in site specific situations (ICRP, 2019; IAEA, 2003). It should be emphasized, especially with respect to operational and regulatory control aspects in industries that the dynamic risk assessment, which comprises of the identification, assessment, and management of risks for safety and health at work, is an already existing concept, largely employed regarding health and safety. Its performing is a legal requirement in Europe according to the Safety and Health Framework Directive 89/391/EEC (EC, 1989, 2021), which obliges employers in Member States to conduct a workplace risk assessment. However, still in practice, exposure to radiation in a NORM context, in this dynamic risk assessment in industries, is often neglected. This neglection may be a result of lack of knowledge and information about NORM of the different involved parties, but also due to missing a

Table 2
Overview of certain processes/conditions of importance for transport and mobilisation of naturally occurring radionuclides (NOR) in the environment.

Process	Description of the process concerning NOR	Reference
Wind erosion *Saltation* *Surface creep* *Suspension*	Radionuclide resuspension by wind	Anspaugh et al., 1975Nicholson, 1989Kajino et al., 2016Rood et al., 2008Whicker et al., 2021
Leaching	Material (rocks, mineral, soil) weathering – mobilisation of radionuclides from the original source and their further behaviour depends on presence of a wide range of factors leading to radionuclide leaching in the environment	Cathles and Apps, 1975Cook et al., 2018 **Monken Fernandes and Franklin, 2001** Vanhoudt et al., 2021
Precipitation	Radionuclides transformation in environmental compartments – radionuclides may leave the main industrial process rapidly, persist in solution and be precipitated by the various mechanisms such as sorption, co-precipitation, ion substitution, redox transformation and many others depending on conditions and industrial activities	Burnett and Elzerman, 2001Cook et al., 2018Koppel et al, 2021Vanhoudt et al., 2021
Seepage	Transport of radionuclides in liquids flowing slowly out of a hole or through existing cracks	Barth et al., 1998Dorozhkin et al., 1997Vandenhove et al., 2006
Transfer to biota and the further trophic chain (including humans)	Transfer of radionuclides to biota may start at the level so called “primary producers” i.e., plants which can incorporate natural radionuclides dissolved in soil solution into their bodies using solar energy. Then, NOR (as well as other elements) can be transferred to the higher levels of trophic chain, including human one.Similar effects of radionuclides intake are also observed, in limited scale, in some bacteria which, for this incorporation, use chemical or thermal energy instead of solar one. In terrestrial environment some portion of radionuclides also can get into trophic chain through drinking of water, inhalation or inadvertent ingestion or interception. In aquatic environment most efficient pathway of radionuclides accumulation in biota is water filtration which is primordial process on which many aquatic organisms are living (zooplankton, molluscs, shellfish) .	Betti et al., 2004Carvalho, 2011IAEA, 2009Mrdakovic Popic et al., 2012Skipperud et al., 2013Vanhoudt et al., 2021
Sedimentation	Upon radionuclide release into the sea or inland water, they are distributed between particulate and dissolved phases in response to their chemical properties or those of the chemical compounds to which they are associated	Heaton and Lambley, 1995Baeza et al., 2011Sanders et al., 2013
Radon exhalation	It may occur in mining activities, oil and gas industry, indoor facilities, but also in the radon prone areas with higher concentration of natural radioactivity in the background, non-altered by human activities	Haanes et al. 2019Magalhães et al., 2003Moed et al. (1998)
Atmospheric dispersion	Movements and transport of airborne radionuclides emitted from different sources such as industry. The radionuclide fate, and thus resulting effective doses, can be different depending on forms of radionuclide and other material forms emitted as dust or vapour, chemical reaction of volatile compounds, meteorological transport, dispersion velocity and direction, deposition of radionuclides, how they are transformed as a result of radioactive decay, interaction with the surface and ecosystems, etc.	Bem et al., 2002Kunze et al., 2019Pettersson and Koperski, 1991.
Dry and wet deposition	Free fall of atmospheric gasses or particulate matter containing radionuclides and washing out of gases containing radionuclides mixed with suspended water in the atmosphere, respectively	Anand and Rangarajan, 1990Kinnersley and Scott, 2001Salminen-Paatero and Paatero, 2021
Human food chain contamination	When NOR are present in non-human biota, animals and plants, the transfer and possibly bioaccumulation can be observed in the food chain with radionuclides coming finally to the man (e.g., fish and molluscs consumption and ^{210}Po intake giving the elevated exposure dose)	Aoun et al., 2015Carvalho, 2011IAEA, 2009Skuterud et al., 2005

properly adapted assessment methodology that would be available and user friendly for the mentioned parties and stakeholder groups with interest in risk assessments. In the RadoNorm project, following the data collection by NORM registers at identified sites, the characterisation of exposure scenarios and steps towards development of an integrated impact assessment procedure, for a general wider use and for different purposes, are aimed for multiple hazards including NOR. In these activities, the existing dynamic risk assessment methodology for other types of hazards will be considered. Having knowledge and understanding of the NRH would allow optimization of management approaches while complying with radiation protection, health, safety and environmental standards.

Therefore, with respect to both research and regulatory aspects, questions that would allow collation of qualitative information about presence of other NRHs at different NORM exposure situations and description of existing protective measures, which will be followed by quantitative data collation at chosen sites, have been included in the NORM registers.

Examples of non-radioactive hazardous substances, identified for some of NORM involving mineral industries and legacies present in Norway, are given in the Table 3 (extracted from the Norwegian Pollution Release and Transfer Register, Norwegian PRTR, 2022).

3.3.5. Dose assessment for workers, public, and non-human biota

Industrial activities involving NORM typically do not give rise to significant doses to workers or members of the public (ICRP, 2019). Most of available literature show radiation exposure doses for workers and public below the dose criterium of 1 mSv y^{-1}, given in the EU BSS and IAEA BSS (e.g., Kunze et al., 2019; Organo and Fenton, 2008). However, there are certain situations, including decommissioning of facilities in oil and gas industry, extraction process of rare earth elements, exposure of workers in water supply facilities due to radon inhalation, work with clean up and remediation of certain NORM affected legacy sites, for which exposure doses may be significant and need to be evaluated, taking into account relevant scenario and exposure pathways (EC, 1999; ICRP, 2019; Kim et al., 2019; Koppel et al., 2021; Shin et al., 2019; Trautmannsheimer et al., 2002).

In practice, the use of models to estimate doses for workers and members of public is a part of the assessment/screening procedure for industries using NORM industries in most European countries (HERCA, 2021). The European Commission published documents *RP 122-part II* (EC, 2002) and *RP 135* (EC, 2003), with specific exposure considerations and dose calculations, for solid NORM residues and NORM effluents, respectively. Most European Countries have used these publications as reference guidelines; however, the final applied solutions are not

Table 3
Examples of non-radioactive hazardous substances identified in certain NORM involving industries and legacy sites.

NORM involving industry	Non-radioactive hazardous substances
Oil and gas industry	Arsenic, anthracene, benzene, benzopyrene, benzofluorene, alkyl-phenols, cadmium, carbon-dioxide, chromium, copper, anthracene, drill-cuttings, dioxins and furans, gas, lead, mercury, nickel, methane, nitrogen oxide, polyaromatic hydrocarbons, pyrene, sulphur oxide, volatile organic compounds, xylene, zinc (over sixty elements and compounds identified)
Mineral industry – phosphate production	Ammonia, carbon dioxide, fluorides, methane, methanol, nickel, nitrogen oxide, particulate matter, total phosphorus, sulphur dioxide, total nitrogen, volatile organic compounds, zinc
Mineral industry – TiO_2 and iron production	Arsenic, cadmium, lead, particulate matter, mercury, zinc, polyaromatic hydrocarbons, sulphur dioxide, dust, chromium, carbon dioxide, copper, iron, manganese, methane, nitrogen oxide, volatile organic compounds
NORM affected legacy site	Arsenic, iron, lead, copper, chromium, nickel, manganese, dust, particulate matter

unified. Moreover, assumptions based on these documents need to be reviewed considering the updates of the relevant scenarios, pathways, and dose conversion factors.

Therefore, in the developed series of registers, for each industry using NORM, questions have been included to collect information regarding considered exposure scenarios, pathways and available estimation of mean effective doses, for purposes of:

1) getting an updated overview of relevant exposure scenarios considered at different NORM sites and estimated effective doses for workers and public, and
2) developing site-specific exposure scenarios for which updating and conducting new estimations/modelling of exposure doses is planned in the RadoNorm project activities.

The questions in registers have been given categorised for workers and for public separately, but include same level of details as mentioned above, which are questions on exposure scenarios, exposure pathways, mean effective doses per pathway and total effective dose for each NORM exposure situation. In order to obtain as many as possible specific scenarios, considered in different countries for various exposure situations, the question on exposure scenario is made as an open question, which gives the possibility to end-users to define scenarios - used from RP 122, part II (EC, 2002), or IAEA SSR-44 (IAEA, 2005) or tailor made scenarios; on the contrary questions on exposure pathways are made as closed questions and include listed possible options that for different exposure scenarios include external exposure to NOR, inhalation, ingestion via food chain contamination, inadvertent ingestion, ^{222}Rn and its decay products inhalation, skin contamination of organisms of concern. When data on mean effective dose per exposure pathway is provided by end-user – a total mean effective dose for given exposure scenario is calculated automatically.

The protection of NHB has become more prevalent in the recent decades (Andersson et al., 2009; ICRP, 2007; 2017; UNSCEAR, 2008). There are many publications showing that NHB may potentially be receiving a radiation dose due to NOR in different industrial or environmental conditions as well as literature highlighting knowledge gaps and need for more research (Hosseini et al., 2012; Mrdakovic Popic et al., 2012; MacIntosh et al., 2022). However, there continues to be conflicting opinions among different involved parties, including researchers, regulators and operators, both at national and international levels. Questions and scepticism have been typically expressed about need on particular regulatory framework for NHB and environmental protection, criteria to be used, anthropocentric versus ecocentric approach in radiation protection, but also about the dose-assessment methodology, the models and parameters to be used in assessments, application of the ecosystem approach in practice, observed NHB effects at existing post accidental situations, such as after Chornobyl or Fukushima event, *et cetera*.

To gain an improved perspective on how radiation exposure of NHB in cases of NORM exposure situations is considered in practice internationally and to identify sites with available data for future investigation of possible effects and NHB dose rates in low dose radiation exposure situations, questions on dose assessment for NHB (i.e., reference animals and plants (RAPs), ICRP (2009)), used dose and risk assessment models and available magnitude of the exposure dose rates are included in the registers. Examples of considered categories are reported in Table 4.

3.3.6. Activity concentration of relevant radionuclides

For each industrial activity involving NORM and other NORM existing exposure situations such as legacy sites and HBRA, quantitative data on activity concentrations of natural radionuclides can be collected by NORM registers. To avoid significant uncertainty in dose evaluation, only parent radionuclides of the most abundant decay series, ^{238}U and ^{232}Th, and data for other radionuclides, including ^{226}Ra, ^{222}Rn, ^{210}Pb, ^{210}Po, ^{228}Ra, ^{228}Th and ^{40}K, are required for raw materials, main and by-products, residues, waste and discharges, for different exposure situations when using different NORM registers. For each radionuclide, data regarding minimum, maximum, mean and median concentrations are requested. The selected radionuclides are those having a half-life long enough to enable them to behave in the process and environment independently from their parents or having physical properties enabling specific migration pathways such as radon. Additionally, radionuclide ^{220}Rn, with a short half-life of 55.8 s (Bé, et al, 2004) was included only in registers for HBRA, legacy sites, mining industry, geothermal energy production and groundwater filtration activity, as it was considered that it can be of concern in these specific conditions.

The collected data are intended to provide a quantitative overview, which will be further used for different case studies and analyses of processes of accumulation, mobilisation and transport of NOR in selected industries and surrounding environments, consideration of reuse possibilities for NORM residues as well as input data to the impact and risk assessment and evaluation of exposure doses and related risk in

Table 4
Categories of reference animals and plants (RAP) and models for dose assessments for non-human biota.

RAPs	Methods used to calculate dose (can be chosen for each of listed RAPs)
Large terrestrial mammal (deer)	ERICA Tool
Small terrestrial mammal (rat)	Direct measurement of external exposure (individual dosimetry)
Large terrestrial plant (pine tree)	External and internal dose calculation via direct biota measurements (in vivo or in vitro)
Small terrestrial plant (grass)	Site specific model
Terrestrial annelid (earthworm)	RESRAD-BIOTA
Terrestrial insect (bee)	*Other (to specify)*
Marine fish (flatfish)	
Marine crustacean (crab)	
Seaweed	
Freshwater fish (trout)	
Amphibian (frog)	
Aquatic bird (duck)	

selected industries using NORM.

Collection of qualitative and quantitative data on legacy contamination will contribute to the decision-making process on remediation options as it will not only provide site characterisation but allow exposure doses modelling for the workers, public and the environment in the different remedial options.

3.3.7. Destination of NORM residues, waste and discharges

Industrial activities involving NORM, as any kind of industry, leads to the creation of a desired product but also residues which may be classified as waste or as material subject to reuse, recycling and recovery. Decision on possibility for reusing or recycling the material is commonly made considering a large set of factors and constraints, such as environmental, health and safety, economical, technical, infrastructure, etc. Enhanced activity concentration of NOR in residues may hinder the reuse and recycling of a given material, due to regulatory considerations and radiation protection. Managing waste in an environmentally sound manner and making use of the residues are key elements of the EU's general environmental policy that should also be applied to NORM residues through reprocessing, recycling and recovery solutions while guaranteeing radiation safety (HERCA, 2021), and in light of circular economy and European Circular Economy Action Plan (EC, 2021) and in accordance with the 2030 Agenda for Sustainable Development (UN, 2015) and European Green Deal (2019).

However, countries worldwide still have different management and regulatory approaches to NORM residues and waste. In some countries NORM waste with NOR activity concentrations above the exemption level of 1 kBq kg^{-1} is considered as radioactive waste, while in some countries such NORM waste in not considered as radioactive waste (HERCA, 2021). As consequence, there may be different requirements for waste management and disposal. Similarly, different approaches to reuse of NORM residues have been observed as well. Exposure scenarios and exposure dose modelling related to NORM residues and waste need to be reconsidered and updated taking into account differences in nationally developed approaches and best practices.

In the developed series of registers, for each NORM involving industry, questions were included to collect information regarding the main destinations and recovery options for NORM residues and waste. Possible drop-down menu answers include non-hazardous landfill, hazardous landfill, inert landfill, dedicated NORM landfill, repository for radioactive waste, sewage system, water bodies – the sea, rivers, lakes, atmosphere; recovery or recovery before disposal options include incineration, reuse, recycling, reprocessing.

At this level of data collection, such information is of importance to achieving a collection of best national practices regarding management options for NORM residue, which will eventually lead to improved management and regulatory approaches to NORM residues and waste internationally. Quantitative data of NOR in residues are expected to allow exposure dose estimations for public and NHB due to effluents and discharge in specific developed exposure scenarios, while data concerning waste will be used to evaluation of exposure doses at different disposal options in different scenarios.

4. Conclusions and perspectives

The main structure and features of a set of registers, developed for qualitative and quantitative data collection in NORM involving industries and at existing environmental exposure situations (legacy and HBRA), are presented in this paper. It is expected that the set of NORM registers, provided as *Microsoft Excel* workbooks, will ensure updated and new data collation and systematisation in a harmonised way, and thus, will provide more ready comparisons between interested countries.

The data may be used both to obtain summary overviews within and among the different industries, as well as be used in more sophisticated analyses to identify trends and effect sizes (which factor has the most effect on the variation in a particular variable). Potentially, both data variables and results may be used in future modelling studies.

Moreover, the results that will be obtained by application of these tools should provide an update of NORM exposure situations throughout Europe and potentially, eventually worldwide. The current work can also be seen as a preparatory work for the development of an international database of NORM in the future and for the preparation of industry-unified dose calculators.

Finally, the developed methodology and register tools could be also helpful for worldwide countries in their dealing with NORM issues.

CRediT authorship contribution statement

Jelena Mrdakovic Popic: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision. **Hallvard Haanes:** Methodology, Writing – review & editing. **Christian Di Carlo:** Methodology. **Cristina Nuccetelli:** Methodology. **Gennaro Venoso:** Methodology, Writing – review & editing, Software. **Federica Leonardi:** Methodology, Writing – review & editing. **Rosabianca Trevisi:** Methodology. **Flavio Trotti:** Methodology. **Raffaella Ugolini:** Methodology. **Alla Dvorzhak:** Methodology, Writing – review & editing. **Alicia Escribano:** Methodology. **Danyl Perez Sanchez:** Methodology. **Almudena Real:** Methodology. **Boguslaw Michalik:** Methodology, Writing – review & editing. **Lea Pannecoucke:** Methodology. **Pascale Blanchart:** Methodology. **Antti Kallio:** Methodology. **Ruth Pereira:** Writing – review & editing. **Joana Lourenço:** Writing – review & editing, Visualization. **Lindis Skipperud:** Validation. **Simon Jerome:** Validation, Writing – review & editing. **Laureline Fevrier:** Methodology, Funding acquisition, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The developed Tools -Excel files are made available as supplementary material.

Acknowledgment

Authors sincerely thank to the anonymous reviewers for their valuable suggestions, which greatly improved the quality of the paper.

This work was done in the frame of the European RadoNorm project. This project has received funding from the Euratom research and training programme 2019–2020 under grant agreement No 900009.

The work was supported also by:

- Polish Minister of Science and Higher Education programme "PMW" (international co-found projects) under grant agreement No 5156/H2020-Euratom/2020/2021/2.
- POPH and national funds (OE), through FCT—Fundação para a Ciência e a Tecnologia, I.P., in the scope of the framework contract foreseen in the numbers 4, 5 and 6 of the Article 23, of the Decree-Law 57/2016, of August 29, changed by Law 57/2017, of July 19. We acknowledge financial support to CESAM by FCT/MCTES (UIDP/50017/2020 + UIDB/50017/2020 + LA/P/0094/2020), through national funds.
- Joana Lourenço was funded by national funds (OE), through FCT—Fundação para a Ciência e a Tecnologia, I.P., in the scope of the framework contract foreseen in the numbers 4, 5 and 6 of the article 23, of the Decree- Law 57/2016, of August 29, changed by Law 57/2017, of July 19. CESAM is a research unit financially

supported by FCT/MCTES (UIDP/50017/2020 and UIDB/50017/2020), through national funds.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.107954.

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