The management of NORM residues – practical aspects

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Abstract. Different types of NORM residues are generated in many industries and most of them require appropriate management. The paper discusses the classification of the materials – especially the differences between “NORM residue” and “NORM waste” and between relevant management strategies. Several practical examples are also provided –
NORM residues:
- Immediate removal for reprocessing, and
- Long-term storage.

NORM waste:
- Long-term storage followed by disposal,
- Concentrate and contain option,
- Delay and decay option, and
- Dilute and disperse option.

Additional information is also provided for the dilute and disperse management option, as in many cases it is selected as the preferred one – both for NORM residues (that are blended with other materials in the process of their re-use), and for NORM waste (as no radiologically contaminated legacy sites are created after blended material is disposed of in mining voids and landfills).

1. INTRODUCTION

NORM occurs in industries either because the activity concentration of naturally occurring radionuclides in the raw materials is higher than average, or because the activity concentration in residues and wastes is enhanced during the processing of the raw materials. There are two main mechanisms by which a radioactive residue could be generated:

(a) Large quantities of raw materials with low radioactivity are directly transformed into small quantities of residues (mass transfer), for example coal combustion;
(b) Small amounts of radioactivity are selectively transferred from large quantities of raw materials into residues (activity transfer), for example precipitation of scales.

Typical examples of the processes of the generation of NORM residues are:
- Radioactive raw materials: phosphate fertilizer and titanium dioxide pigment production,
- Precipitation: generation of scales and sludges in oil/gas production and in water treatment,
- Volatilization: filter dust from coal combustion and metal smelters,
- Radioactive products: magnesium-thorium alloys, refractories.

2. NORM RESIDUE MANAGEMENT – PRACTICAL APPLICATION

2.1. Definitions

The first step in the management of NORM residues is their classification, in accordance with the requirements of the IAEA Basic Safety Standards (paragraph I.4 and Table I.3), and the application of graded approach (Requirement 6) [1]. The additional information on the application of values is given in Part 5 of the IAEA Safety Guide on exclusion, exemption and clearance [2].

The next step is to define both residue and waste, in accordance with the Safety Glossary [3]:
- *NORM waste. Naturally occurring radioactive material for which no further use is foreseen.*
- *NORM residue. Material that remains from a process and comprises or is contaminated by naturally occurring radioactive material (NORM).*
  A NORM residue may or may not be waste.

Therefore, there is a need to establish if there is any further use for a NORM residue.
It is important to bear in mind that this assessment should take into account not only current circumstances, but also future estimates. The fact that there is no use for a NORM residue at the current moment does not mean that the material has to be classified as waste. If:

(a) The use of the material in the future is *foreseen*, and
(b) This fact can be proven to the satisfaction of all relevant regulatory authorities –

The material could be classified as residue and a long-term strategy for the management of its temporary storage – developed.

2.2. General aspects of NORM residues management

The following general requirements apply to the management of NORM residues:

- A national policy framework within which NORM residues are managed;
- A strategy for the implementation of this policy, including the provision of necessary resources;
- An appropriate national legal and organisational framework within which NORM residue management activities can be planned and carried out safely.

The national policy and strategy should ensure that the management system for NORM residues is consistent with management systems and requirements for residues from other industrial processes. This is very important as NORM residues commonly contain non-radioactive constituents that may be hazardous. The national policy should also ensure that the management, storage and disposal of NORM-contaminated items are taken into account.

A typical management framework would comprise the following:

- A Member State should determine which industries within its jurisdiction are concerned with the processing of NORM and generating NORM residues, including a *national inventory* of legacy sites, i.e. sites containing NORM residues from discontinued past practices;
- The regulatory body should have a good understanding of the technical and financial circumstances of the operator of each facility;
- The operators must have sufficient financial and human resources to enable not only safe and efficient management of NORM residues, but also a capability to manage all decommissioning and remediation activities.

It is extremely important to ensure that non-radiological contaminants that may be present in NORM residue or waste are taken into account in the development of a management strategy. The impacts of non-radiological contaminants are very often as important as radiological impacts. The understanding of non-radiological parameters may also be necessary to understand the environmental processes in the dispersion of radioactive contaminations (e.g. pH, ground water gradient, etc.). Additionally, non-radiological contaminants can be used as analogues for radioactive contaminants (e.g. natural lead for ^{210}Pb, where there is a direct relationship).

2.3. Options for the management of NORM residue

The management of NORM residues depends on when they would be re-used:

- If the residue is transferred to a re-use/recycling facility as it is being generated, the usual strategies for the management of the processing of a radioactive material will be applicable – as the residue generated at one facility will be considered as a "raw material' at another facility.
- If it is expected that the NORM residue will need to be stored for a period of time before re-use, it will need to be placed into an authorised storage facility – sometimes requiring the development of a long-term management plan.

Several typical residues generated in different industries and the possibilities for their re-use are summarised in Table 1.

Table 1. Some NORM residues and options for their re-use

NORM residue	Products and/or re-use options
Small amounts of metals – surface contaminated	Scrap metal recycling
Phosphogypsum	Soil improvement, fertiliser Building materials Landfill cover Water purification Road construction
Slags	Road construction
Mining tailings	Underground or open pit backfill
Waste rock	Construction material for tailings storage facilities and roads on mining sites
Fly ash Bottom ash	Road construction Inclusion in cement and concrete Fertiliser and soil conditioner
Heavy mineral sands processing tailings Red mud from bauxite processing tailings	Open pit backfill
Contaminated plastic, wood and rubber	A clear reuse option has not yet been found
Filter masses and filter cloths from water treatment, processing of titanium, rare earths, copper and other minerals	
Scale and sludge from oil and gas exploration and production (including hydraulic fracturing), and from geothermal energy generation	

Examples of the management of NORM residues are given in Part 3.

2.4. Options for the management of NORM waste

The issues with NORM waste have been discussed at the very first NORM Symposium in 1997, the following approaches were proposed for the management of NORM waste [4] and most of them are being used today: shallow land or underground burial, interim storage, diluting or spreading, recycling.

There are currently four different options for the management of NORM residues after it has been decided that no future for them is foreseen and therefore, they have been classified as waste. Examples of the management of different types of NORM waste are given in Part 4, for:

(a) Long-term storage followed by the disposal,
(b) "Concentrate and contain" option,
(c) "Delay and decay" option,
(d) "Dilute and disperse" option.

3. MANAGEMENT OF NORM RESIDUES

In almost all known cases of the re-use of NORM residues the material is utilised as an additive to another product to improve its quality. Please note that the same blending process takes place during the dilution of NORM waste with non-radioactive materials prior to the disposal (Part 4.4), but in that other case the aim is to ensure that there are no restrictions on the future use of the disposal site.

3.1. Immediate removal of NORM residues from a site for reprocessing

A product called silica fume (SiO_2) is generated in the production of zirconia (ZrO_2) from the mineral zircon ($ZrSiO_4$). This residue is typically generated in low quantities, in order of several tons per month and as soon a reasonable amount of it has been accumulated on the site, it is transported to a customer, typically every several weeks.

As noted in the IAEA Safety Report [5], in the process of fusion of zircon ^{238}U and ^{232}Th tend to stay with zirconia, but ^{226}Ra, ^{210}Pb and ^{210}Po tend to end up in the silica. As IAEA Safety Report further states, the fine-grained silica produced in the zircon fusion process is usually sold as a by-product for use as an additive to cement and in brick making.
The concentrations of ^{226}Ra in silica fume are reported to be in order of 5.8 Bq/g [6] and, as has been confirmed in several unpublished studies, concentrations of ^{210}Pb and ^{210}Po are typically of the same order. Therefore, the care is always taken to ensure that final materials (such as cement) do not contain more than 8-10% of silica fume.

In another case silica fume is considered to be a waste, details are provided in Part 4.4.

3.2. Long term NORM residues storage

When a NORM residue cannot be utilised in the near future, an assessment is made to ascertain if the material would be a valuable resource in the future. Two cases from Australia can serve as examples when the use for the NORM residue has been found after a considerable amount of time.

3.2.1. Monazite concentrates

When the production of monazite in Australia ceased in mid-1990’s due to the market conditions, most of the companies processing heavy mineral sands opted for the ‘dilute and disperse’ option for this material, described in Part 4.4. One company, however, was able to prove to all relevant government departments that the temporary storage of monazite concentrates (containing 90-110 Bq/g of ^{232}Th and 10-15 Bq/g of ^{238}U) at the site that was classified as “arid” and “remote” will not cause any measurable impacts on the public and the environment. It is considered that the selected strategy was correct, as:

- The mineral monazite contains significant concentrations of rare earth elements – thus it is considered to be a valuable resource and some sales of monazite concentrates have already occurred, and
- Even in the case when all accumulated material would not be sold in the intermediate future (next 20-30 years), the temporary storage location was selected in such a way that it could be converted into a long-term storage by simply covering the material in the mined out pit and having this valuable resource available to future generations.

3.2.2. Neutralised used acid

Neutralised used acid (NUA, also called synthetic gypsum) is generated in the production of the synthetic rutile from titanium mineral ilmenite and typically contains 0.5-0.7 Bq/g of ^{232}Th and 0.2-0.3 Bq/g of ^{238}U. This product is a mixture of iron oxides, hydroxides and other iron-containing substances (~30-35%), gypsum ($CaSO_4$ ~60%), with minor quantities of quartz (~5%) and manganese (~3%).

The concentrations values are below those at which regulatory control may be considered in accordance with the IAEA BSS [1], but due to the fact that the product may be used in agriculture a radiological impact assessment is usually required.

This NORM residue has been stored at one of the mineral processing sites in Western Australia for several years until the application has been found: the NUA is mixed at a 5% ratio with inert sand to construct a “nutrient filter” in order to enhance soluble phosphorus removal from the surface water streams. In two years since the nutrient filter has been constructed, no changes in concentrations of NORM have been detected in the surrounding area, in water, soil and vegetation – it is expected that the application of nutrient filters could possibly be extended to other constructed wetland basins in the area.

4. MANAGEMENT OF NORM WASTES

4.1. Long term NORM waste storage followed by disposal

As described in part 3.2, in many cases NORM residues are stored for a considerable amount of time before the use for them is found. However, relatively often the materials could not be utilised during the lifetime of operations or in the intermediate future and are, therefore, classified as waste requiring appropriate disposal.

4.1.1. Phosphogypsum

Very large volumes of phosphogypsum ($CaSO_4 \cdot 2H_2O$) have been generated by the phosphate industry [7, 8]. As reported by the IAEA [8], 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. This has resulted in phosphogypsum stacks being, in effect, turned from short-term holding piles into long-term disposal facilities. It has been estimated that, by 2006, a total of 2.6–3.7 billion tons of phosphogypsum had been accumulated in stacks worldwide.
The concentrations of radionuclides in phosphogypsum may range between 0.01 and 0.50 Bq/g of ^{238}U and between 0.02 and 3.20 Bq/g of ^{226}Ra. Therefore, in some cases specific protection measures may be required for the disposal of this material [8].

4.1.2. Tailings from the processing of titanium minerals

In the production of synthetic rutile from titanium minerals iron is removed from ilmenite, thus increasing titanium content from 40-60% to approximately 90% [9]. A modification of this process involves the addition of a specific flux – NORM radionuclides migrate to this flux, resulting in tailings containing NORM in concentrations that require management [1].
The radionuclides such as ^{228}Ra and ^{226}Ra become relatively mobile in the tailings from this process and must be deposited in the specifically engineered lined tailings storage facilities. In almost all cases no future use for these tailings is foreseen and they are classified as waste.

At one of the locations in Australia due to the urban encroachment the tailings dams with these materials are now located in a close vicinity of residential areas, which poses a significant problem:

- On one hand, the likely impact of these tailings on the environment and the general public is expected to be small, and the relocation of these tailings to a mine site may be very expensive.
- On the other hand, the location of the "radiologically contaminated site" in a close vicinity of residential areas may not be acceptable from the public perception point of view and the company may have no choice but to relocate radioactive material to the mine site, where specifically engineered tailings disposal facility will need to be constructed.

At the moment the final solution has not yet been found, as the company wishes to retain the tailings at their current location. However, an appropriate authority is likely to be of the opposite opinion, as the tailings are stored at the location that was not suitable even at the time when the tailings storage facility has commenced operations, in accordance with the relevant Australian Code of Practice [10] and, therefore, applicable regulations [11].

4.1.3. Processing tailings

At a medium-size mineral processing plant in Asia the tailings containing approximately 9 Bq/g of ^{232}Th, 1 Bq/g of ^{238}U, 8 Bq/g of ^{228}Ra and 2 Bq/g of ^{226}Ra are generated at a rate of approximately 90,000 tonnes per year. When the plant was constructed, the use for this NORM residue has been found as an additive to the road construction materials and it was stored for two years whilst the final testing of the re-use of the residues was carried out.

This NORM residue has been re-classified as waste and re-use project was abandoned for the reason that is very important in the utilisation of all NORM residues:

- Almost one million tonnes of “clean fill” was needed to be purchased annually for blending purposes – to ensure that the final mix will not require radiological management in accordance with the regulations applicable in the country,
- Even if such volume of “clean fill” would have been available at a very low cost – the project was not feasible, as only 15-20% of the NORM residue could have been utilised for the construction of necessary roads in this country; there was simply no need for such large volumes of road construction material in the area where the plant is located.

4.2. Concentrate and contain option

This option is utilised in cases where the volumes of NORM waste are relatively small, but the concentrations of radionuclides are relatively high.

4.2.1. Oil and gas industry

In the oil and gas industry concentration of ^{226}Ra in scales inside pipes and different valves can reach or exceed 15,000 Bq/g and in sludges – 800 Bq/g [12]. The scales are removed at special NORM treatment plants and are typically compacted into drums that are kept in a controlled area and then disposed of in authorised facilities.

4.2.2. Titanium dioxide pigment industry

In the titanium dioxide pigment industry radionuclide activity concentrations measured in scale and discarded filter cloths can sometimes exceed 1,500 Bq/g of ^{228}Ra and ^{228}Th [9]. The scales and filter cloths are relatively small in volume and are typically kept in dedicated sheds/containers prior to the disposal into an authorised facility.

4.2.3. Decommissioning of NORM facilities

In the process of decommissioning of NORM facilities one of the main aims is to ensure that the valuable equipment such as pumps, tanks, conveyors etc. are decontaminated to the levels allowing for this equipment to be re-used in other industries. The decontamination process always results in the generation of NORM waste – most often the water used for high pressure blasting would contain insoluble particles. When this water is recycled through a filter a relatively small volume of NORM waste is generated, which will require an appropriate disposal.

Another process in decommissioning that may result in a generation of a NORM waste is the draining of processing vessels – in one of the cases in Australia sulphuric acid was recycled over several years in the processing of a mineral containing not more than 2 Bq/g of ^{226}Ra. When the acid was drained and dried the concentrations of ^{226}Ra in the resulting residue were found to be over 2,000 Bq/g.

4.3. Delay and decay option

This option is used relatively rarely, as most NORM radionuclides have very long half-lives. There are, however, two notable examples.

4.3.1. Dust containing ^{210}Po

The dust collected by electrostatic precipitators at different smelters (iron, nickel, copper) may contain significant concentrations of ^{210}Po. In cases where this dust does not contain other toxic contaminants and the concentration of ^{210}Po is the only limiting factor for the disposal of this material at the industrial landfill, the “delay and decay” approach is typically taken.

For example, the dust containing 300 Bq/g of ^{210}Po (half-live of 140 days) will contain less than 10 Bq/g of this radionuclide in 22 months, and the material will be exempt from radiation safety regulations in accordance with the Table I.3. of the IAEA BSS [1] (less than 1 Bq/g) in just over three years.

Relatively often this dust would also contain ^{210}Pb with much longer half-life (22 years). In these cases the "delay and decay" option would require a long term management plan for the material, described in part 4.1.

4.3.2. Processing tailings containing ^{228}Ra

The similar "delay and decay" approach was taken by one of the mineral processing companies, generating waste stream with ^{228}Ra activity concentration of 7 Bq/g (the parent radionuclide ^{232}Th reports to another tailings stream).

This waste could be disposed into an industrial landfill when the concentration of ^{228}Ra is below 1 Bq/g, in accordance with Table I.3 of the IAEA BSS [1]. The original ^{228}Ra activity concentration of 7 Bq/g falls under the activity concentration limit of 1 Bq/g after 17 years.

4.4. Dilute and disperse option

4.4.1. Silica fume

Silica fume that was described in part 3.1 above was considered to be a waste material in the UK and disposed as an industrial waste to a local landfill until 1991, when the analysis of the material indicated that it contains 30 Bq/g of ^{226}Ra, 200 Bq/g of ^{210}Pb and 600 Bq/g of ^{210}Po [13].

Despite the fact that all environmental assessments indicated that the risks to the public and the environment are minimal, none of the disposal sites agreed to accept this NORM waste. The only possible way to dispose this material was found to be blending it with damp sand to the levels when the material is exempt from the radiation protection regulations. Then a landfill site is not required to obtain the license to dispose of radioactive material.

4.4.2. Monazite concentrates

Monazite concentrates that were described in part 3.2.1 above were commonly disposed of in Western Australia in mined out pits after blending with non-radioactive materials, in accordance with applicable regulation [14] that states –
Each responsible person at a mine site must ensure that, so far as is practicable, radioactive waste is diluted with other mined material before it is finally disposed of in order to ensure that in the long term the use of the disposal site is not restricted.

Monazite concentrates containing approximately 100 Bq/g of ^{232}Th and 12 Bq/g of ^{238}U are transported to a mine site where they are blended thoroughly with mine tailings (sands and slimes, containing only trace amounts of NORM) [15]. The final tailings stream for the disposal contains only 0.4-0.6 Bq/g of ^{232}Th (^{238}U is typically below the limit of detection). Therefore, no 'legacy sites' that would require institutional control for a very long period of time are created.

5. DILUTE AND DISPERSE (BLENDING) OPTION ADDITIONAL COMMENTS

As the "dilute and disperse" management option is considered to be the most controversial one – an additional discussion of it is warranted.

The IAEA Fundamental Safety Principle 7 [16] states that –
3.29. Radioactive waste must be managed in such a way as to avoid imposing an undue burden on future generations; that is, the generations that produce the waste have to seek and apply safe,

practicable and environmentally acceptable solutions for its long-term management. The generation of radioactive waste must be kept to the minimum practicable level by means of appropriate design measures and procedures, such as the recycling and reuse of material.
Therefore, reuse and recycle of radioactive waste needs to be considered in each case.

Different IAEA documents provide additional information and recommendations in regards to this waste management option. Definition of dilution is:
Dilution is the process in which a contaminant becomes less concentrated. It is similar for both organic and inorganic contaminants, including radionuclides. It reduces risk because resulting exposures will be lower. By itself, however, dilution does not reduce contaminant mass; rather it spreads the area of potential exposure. [17]

Observations from different IAEA documents in regards to this management method are as follows:

- *The problem is aggravated by accumulating effects along the food chain. Another uncertainty that to date remains unresolved is the potential effect of prolonged exposure to very low concentrations. In the light of these concerns, discharges and releases have been prohibited (declared radioactive waste) or significantly curtailed in some regions of the world through international agreements* [18].
- *There is no doubt that, even where not proscribed by legislation, the dilute and disperse option is opposed by regulators, environmental groups and the public at large* [19].
- *Dilution needs to be used sensitively in order to demonstrate implementer credibility and ethics in the management of radioactive waste and thereby maintain public acceptance. Nevertheless, it is a potentially valuable technique in appropriate situations and has been used successfully* [20].
- *Some legal options for NORM residue disposal might include the release and dilution of residues into water bodies, incorporation back into the natural environment or underground placement* [21].
- *Dilution as a means of increasing the amounts of NORM residues that can be used as by-products should not only be permitted in terms of the national approach, but should actually be encouraged* [22].

It is, therefore, clear that dilution/blending of both NORM residues and NORM waste is the option that needs to be followed, where National regulations allow this practice. This way of the management of radioactive waste is the preferred one in Western Australia [14] and in The Netherlands: *The by-product use of NORM residues is the primary target of a NORM residue management system. For application in civil engineering, a specific requirement in Dutch legislation is that the NORM residue is diluted to a level such that it is no longer considered radioactive (in that it does not exceed the relevant 'exemption' level). Thus, dilution in this case is not only a treatment option but also a legal obligation. Only if the options of recycling or use are not feasible can the material be disposed of, and only then is it considered to be waste* [23].

If National regulations allow, it is recommended that this option is followed – but the possibilities of over-regulation in its application should also be considered.

Unfortunately, it is not uncommon to hear an argument based on "an interpretation of an appendix of a guideline for a procedure that describes a regulation relevant to a section of an Act". It is typically more practical to set the "release" or "re-use" limits for different branches of the minerals industry and leave it to the industry itself to develop technical systems to meet these standards in specific circumstances [24].

It is very important to bear in mind that when a regulatory agency gets involved in writing detailed and compulsory specifications on how to meet the performance standards, there is a danger that the system of radiation protection will degenerate into a continuing industry effort to comply with ever more complicated regulations, procedures and guidelines – completely losing sight of the basic goal of safe operation. [25].

Numerous guidelines on re-use of NORM residues (providing specific "re-use limits") have been produced at a National level. If the regulations in a particular jurisdiction do not prohibit dilution/blending, the guidelines from the European Union [26, 27], Poland [28], Finland [29], People's Republic of China [30, 31], Azerbaijan [32], Tajikistan [33], and Western Australia [34] can serve as useful examples. It should be noted the first available document discussing the use of different coefficients for the estimation of doses and for the possible re-use of NORM residues in building industry was published by the OECD more than 35 years ago, in 1979 [35].

6. CONCLUSIONS

The main conclusion is that, unfortunately, there is still more confusion than certainty in the management of NORM residues and wastes, and the situation has not improved significantly since 1999 [36] and 2007 [37].

Despite the best efforts of the International Atomic Energy Agency, the Safety Reports issued for the different industries remain unknown and unused by the industries for which they were intended. A clear illustration of the issue could be drawn from the number of industry representatives attending international NORM symposia.

The participation of zircon, titanium, and rare earth industries in the three latest international NORM congresses was:

- NORM-V, Spain, 2007: nine out of 202
- NORM-VI, Morocco, 2010: zero out of 142
- NORM-VII, China, 2013: zero out of 176

The importance of the participation of the industry in the NORM congresses is not well understood, and it appears that different branches of mining and mineral processing industry voluntarily exclude themselves from the early stages of regulatory process that will directly affect their operations in the near future.

a. There are many different options for managing various types of NORM residue and NORM waste – the selection of a method would depend not only on technical and economic considerations, but also on what options are allowed by the regulations applicable in the particular jurisdiction, and on public opinion.
b. A possible management method typically cannot be based on a limit of activity concentration, due to the large variety of NORM residues and wastes and possible migration of different radionuclides into the environment. However, industry- or substance-specific guidelines may be developed.
c. Additional approvals from an appropriate authority will be required in each case, based on a separate radiological impact assessment carried out for all reasonably possible scenarios.

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