Management of Operational and Existing Exposure Situations Due to NORM and Natural Radiation: Radiation Protection and Scientific Challenges

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Abstract

Almost every country has NORM industries and legacy sites from past operations, and many materials (mineral ores, commodities, products, waste and residues) containing NORM that require some level of management to avoid unnecessary exposures. An example of a legacy situation is the South Alligator River Valley (Northern Territory, Australia) where there are a number of abandoned uranium mine sites. The radiation protection community has to develop procedures for managing a very wide range of situations in a systematic way, based on sound, defensible principles, and consistent with international best practice. Ideally, these should include an internationally harmonised regulatory approach to avoid trade issues (commodities and products). Experience in NORM industries and in dealing with management of NORM wastes and residues and legacy sites also suggests that regulation of NORM should be based on a graded approach (level of regulatory control based on assessed risk). NORM management procedures have to be cost-effective, particularly in view of the large quantities of material involved. Stakeholder involvement is critically important, because lifestyles, jobs, etc, can be affected by regulatory and management decisions. Finally any approach that is adopted should solve today's problems in a way that does not leave worse problems for the future.

Key Words: NORM, operational, existing, management, assessment

1 Introduction

This paper mainly discusses the current situation with respect to management of NORM and legacy sites. The challenges posed by the new recommendations of the International Commission on Radiological Protection (ICRP 2008) and the revised Basic Safety Standards (IAEA 2011) are considered in Section 9.

Almost every country has NORM industries and legacy sites from past operations, and many materials (mineral ores, commodities, products, waste and residues) containing NORM that require some level of management to avoid unnecessary exposures.

The first approach to describing these situations was to use the terms NORM (naturally occurring radioactive material) and TENORM (technologically enhanced NORM), with TENORM used to describe materials in which the original radionuclide concentrations had been changed as the result of human actions (e.g. extraction and processing of mineral ores). This is not particularly useful, because NORM defined in this way includes not only materials such as soil, rocks, surface water, ground water and seawater, but also living matter (humans, non-human biota, etc).

It was found more useful to define NORM as material containing predominantly naturally occurring radionuclides where the radionuclide concentrations have been changed from their original values by human action (IAEA 2006). This excludes the undisturbed natural background and other materials that are not amenable to control. Naturally occurring radionuclides include the three primordial decay series, uranium-238 (U-238), uranium-235 (U-235) and thorium-232 (Th-232), and individual nuclides such as potassium-40 (K-40) which have extremely long half-lives. The primordial decay series are characterised by the extremely long half-lives of the parent nuclides.

NORM occurs in a wide range of industries. A list of some of these industries, the associated NORM and the radionuclides of interest is given in Table 1.

Table 1: Some NORM industries, the corresponding NORM generated, and the important radionuclides

MINERAL EXTRACTION AND PROCESSING	NORM	RADIONUCLIDES
Uranium mining and milling	waste rock, tailings, product	U-238 series
Mineral sands mining and processing	waste rock, tailings, product	Th-232 series
Metalliferous ores (copper, tin/tantalum,)	waste rock, tailings, product	All
Bauxite/aluminium mining and processing	Mud residue (red mud)	Th-232 series
Coal extraction and electricity generation	fly ash, bottom ash	All
Oil and gas production	Scales	radium
Phosphate industry	fertiliser (product) phosphogypsum	uranium radium
Building industry	phosphogypsum, alum shale, fly ash	U-238 series
Rare earth production	TiO_2, zircon, zirconia	U-238 series
Scrap metal recycling		
Iron and steel production	Slags	U-238 series
Water treatment	Flocculent	U-238 series

The stages involved in the operation of mineral extraction and processing facilities are shown in very simple form in Figure 1. Although most of the raw materials contain low concentrations of radionuclides, the extraction and processing of mineral ores can produce significantly higher radionuclide concentrations in the waste and residue streams (and sometimes in products). The wastes and residues can also contain elevated levels of other contaminants (chemicals, heavy metals). The management of the wastes and residues is discussed in the next section.

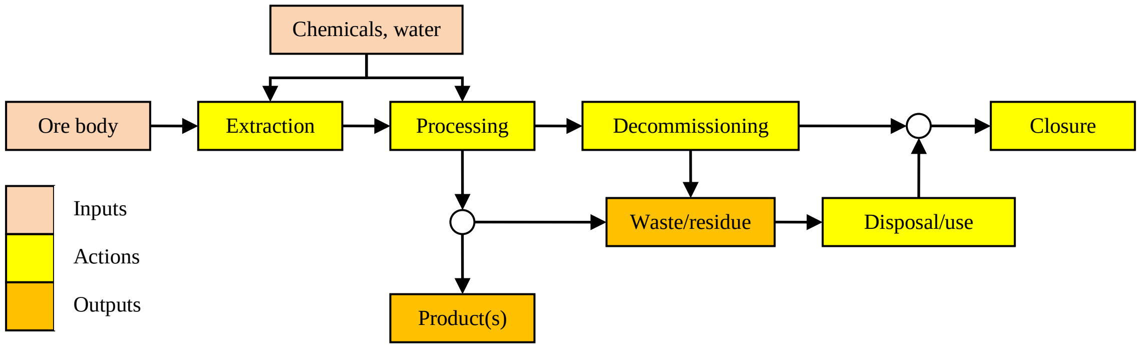

Figure 1: A simplified representation of a mineral extraction and processing facility.

2 Current NORM situations

Awareness of NORM as a potentially significant radiological hazard is relatively recent. One consequence of this, particularly in the mineral extraction and processing industries, is that many early mines and mills operated without any form of regulatory control, and operators made no attempt to restore the sites to a condition that would not require any further action when operations ceased.

Two very different early examples of existing situations involving NORM are houses built using alum shale in Scandinavia, and the abandoned uranium mines in the South Alligator Valley, Northern Territory, Australia. Alum shale was used in Sweden as a source of uranium (Dyni 2006). The waste rock was then used as a building material. In Norway, radon from alum shale has been a significant problem (Stranden 1988). Thirteen small uranium mines operated (without any regulatory control) in the South Alligator River Valley between 1950 and 1960. These were abandoned when operation ceased, resulting in legacy sites that have since required remedial action because of economic (tourism) and cultural issues (Waggitt 2002).

Similar problems have occurred in many countries, leading to a large number of existing situations and legacy sites that may require remediation. The growth of urban areas on and around the contaminated sites, the presence of other non-radiological contaminants, such as heavy metals and chemicals, and the extremely long half-lives of the uranium isotopes, can make remediation of such situations difficult and expensive. In general, the extremely long time scales make it difficult to prevent long-term releases of radionuclides from NORM wastes/residues to the environment.

3 Perception

Perception is very important when discussing the risks associated with ionizing radiation. Labelling of NORM products/commodities as “radioactive” can lead to trade restrictions; this situation is frequently exacerbated due to poor labelling and different legislative and regulatory approaches in different countries. In Australia, many people consider that ionizing radiation is highly dangerous and that there is no safe level of exposure to ionizing radiation, but spend considerable time exposing themselves to solar UV radiation. However, the existence of natural background radiation means that there is no zero level of exposure to ionizing radiation, so that the concept of “no safe level of radiation” is inappropriate when dealing with NORM, while evidence shows that Australia has the highest rate of skin cancer in the world (AIHW and AACR 2004).

4 Management of existing situations/legacy sites

There are numerous examples of poorly sited and/or poorly designed facilities that have been constructed in the past for containment of NORM wastes. An example of a legacy site containing uranium mining wastes is shown in Figure 2. This facility is sited so close to the sea that a breakdown of the containment would release very large quantities of material to the marine environment. The situation could be exacerbated if the waste contains significant levels of chemical contaminants.

Figure 2: A coastal legacy site.

4.1 General assessment methodology (EMRAS II)

The *Environmental Modelling for Radiation Safety* (EMRAS II) working group on “Legacy Sites and NORM” (IAEA 2012) has developed a general assessment methodology for use with sites such as the one shown in Figure 2. A simplified outline of the methodology is shown in Figure 3. This methodology emphasises communication with stakeholders and overall efficiency (“as simple as possible, as complex as necessary”). The approach has been applied to the Søve mining complex in Norway (Brown et al 2011).

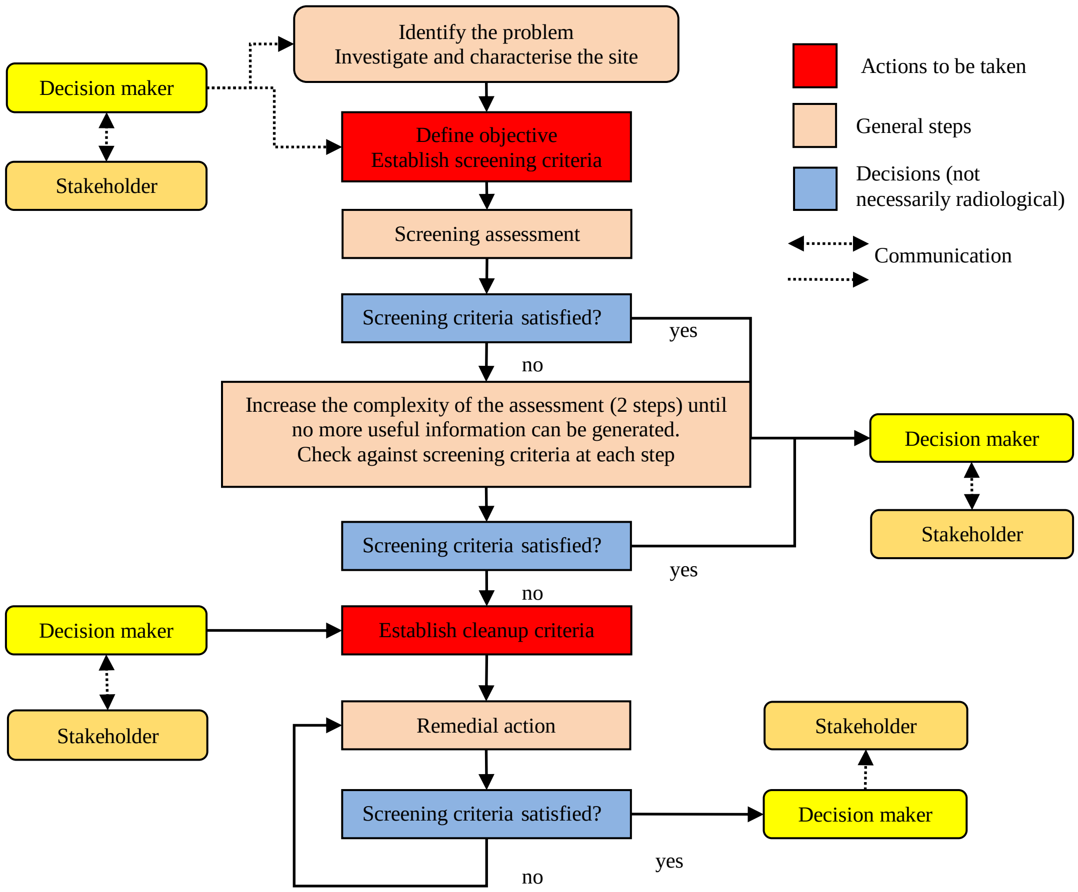

Figure 3: A general methodology for assessment/management of existing situations/legacy sites.

5 Operational Situations - management of NORM wastes and residues

The discussion in Section 2 shows clearly that careful management of operational situations is required, to avoid creating problems for the future.

The radiological risks associated with NORM are generally low, but require management for a number of reasons. NORM wastes/residues can contain elevated concentrations of very long-lived radionuclides and non-radiological contaminants, and most of these materials are usually generated in large volumes. Whatever option is selected for management of these materials, careful assessment of the potential long-term impact is essential.

The principles of radioactive waste management include immobilisation and isolation of the waste from the environment for as long as necessary for the radiological risk associated with the waste to be reduced to an acceptable level. However, for NORM wastes/residues the time required for this reduction in risk is so long that man-made barriers are highly likely to undergo significant degradation. For example, even if all the uranium is extracted from uranium ore, the waste will still contain thorium-230, which has a half-life of approximately 75,000 years.

For these reasons long-term storage of such materials is not a practical management option. It should always be assumed when disposing of NORM waste that radionuclides (and possibly other contaminants) will be released to the environment in the long term. This release of contaminants can be significantly delayed by solidifying the waste, and the long-term impact can be limited by placing a limit on the radionuclide concentrations in the waste. The potential impact of non-radiological contaminants can be significantly reduced by suitable treatment of the waste before disposal.

A salutary reminder of what can go wrong is the situation that occurred near Ajka in Hungary in 2010, where the collapse of a containment barrier released over a million tonnes of caustic liquid waste (red mud) to the environment, causing wide spread contamination (Ruyters et al 2011).

Two obvious methods of disposal for NORM wastes/residues are surface landfill and near surface disposal. However, large areas of land are usually required, other (non-radiological) contaminants may be present in the wastes, and possible future uses of the land need to be taken into account. Therefore the long-term risks and economic and societal costs associated with these disposal methods need to be carefully assessed.

All these considerations mean that there are strong economic incentives to use NORM residues wherever possible. Examples of this include the use of red mud for soil beneficiation (Cooper et al 1995), the use of phosphogypsum and fly ash in building materials, and the use of zircon glazes on ceramic tiles. However, since these materials may contain elevated radionuclide concentrations, the possible risks associated with such use should be carefully assessed (O'Brien et al 1995, O'Brien 1997, O'Brien et al 1998).

Inappropriate use of NORM wastes can also lead to problems. An example of this is the use of uranium mine wastes in dwellings in the Navajo Nation in New Mexico (USEPA 2012). This has resulted in serious health effects and required a costly remediation program.

Urban development on residual contamination around the site of a former thorium gas mantle fabrication facility in Camden, New Jersey, has also necessitated a costly remediation program (USEPA 1999).

All these considerations show that the radiation protection (RP) community and regulators have to develop procedures for managing a very wide range of situations in a systematic way, based on sound, defensible principles, and consistent with international best practice. Ideally, these should include an internationally harmonised regulatory approach to avoid trade issues (commodities and products).

Experience in NORM industries and management of NORM wastes/residues and legacy sites also suggests that regulation of NORM should be based on a graded approach, in which the level of regulatory control is based on assessed risk. Regulation can be an expensive process, for both operators and regulators. An example of this approach is outlined in ARPANSA (2008).

NORM management procedures must be cost-effective, particularly in view of the large quantities of material involved, and the potential societal impacts. Development of such procedures should involve all stakeholders (managers, operators, regulators, public, etc), to optimise the overall outcome.

6 Existing natural radiation situations

The International Commission on Radiological Protection (ICRP) recommended approach to radiation protection is based on justification, optimisation of protection, and application of dose limits. In its 2007 Recommendations the ICRP "emphasises the optimisation of protection regardless of the type of source, exposure situation, or exposed individual" (ICRP 2008). In the same document it was also stated that "In protecting individuals from the harmful effects of ionising radiation, it is the control (in the sense of restriction) of radiation doses that is important, no matter what the source."

The International Atomic Energy Agency (IAEA) approach to regulation is based on the principles of exclusion, exemption and clearance (IAEA 1996). Situations that are not amenable to control should be excluded from regulatory interest. The undisturbed natural background radiation is one of these situations; this depends strongly on local rock and soil types and varies considerably with location.

In principle it is possible to limit exposures to natural background radiation by restricting working hours (e.g. in the airline industry), or by restricting access to areas of high background. However, large numbers of people live in areas where background levels are significantly higher than the average, and there is little if any evidence of elevated radiation-induced health effects in these areas. Relocating these people could have serious economic and social impacts. This suggests that optimisation may be more effective than dose limitation for dealing with NORM and natural radiation.

7 Impact assessment for existing situations (NORM and natural radiation)

When assessing the impact of situations involving NORM and natural radiation, the same approach is generally used for both planned and existing situations. Reasons for assessing the impact of a planned or existing situation include demonstration of compliance with regulatory requirements, estimation of existing impact, estimation of future impact, assessment of the need for remediation (reduction of future impact), and assessment of the need for regulation (current and future impact).

Assessment of situations involving NORM and natural radiation is not the same as assessment of situations involving anthropogenic radionuclides for a number of reasons. The very long half-lives of the naturally occurring radionuclides require assessment of future impacts well beyond any possible active control period for a site. The effects of secular disequilibrium between radionuclides in the same decay series also have to be considered. NORM can exist as solid, liquid or gas; even if only solids are considered, there is a very wide range of materials, with a wide range of chemical properties. There is also a wide range of site and environmental conditions to consider. And finally, the effect of variations in the natural background may have to be taken into account.

For any given situation (e.g. a contaminated site), what has to be considered is the dose contribution resulting from the action that led to the situation. However (see **Error! Reference source not found.**), the total exposure can include contributions from the undisturbed natural background and previous activities on the site.

	SITUATION			
EXPOSURE	PLANNED	EXISTING	EMERGENCY	CONTROLLABLE?
Due to current situation – the impact of this exposure is to be assessed	New exposure (controlled)	Contaminated site	Uncontrolled release	Amenable to control
Due to previous human activities (building materials, landfill, roadfill, waste, .)	Mostly NORM	Mostly NORM	Mostly NORM	Amenable to control
Due to natural (undisturbed) background	Undisturbed background	Undisturbed background	Undisturbed background	Not amenable to control

Figure 4: The components of the total exposure for planned, existing and emergency situations (see text for explanation).

The approach to assessment in this type of situation is best shown by an example. Consider a site where fly ash from a coal-fired power station has been emplaced, and suppose that after several years a group of local residents sues the power company on the grounds that the fly ash has caused significant health detriment to the local community. During the court proceedings it is established that low-level radioactive waste had been placed on the site as landfill before construction of the power station. The problem for the assessment expert is to isolate the impact of the fly ash from the effects of the previously emplaced low level waste and the undisturbed background.

The argument outlined in the Appendix shows that by using linear models it is possible to assess the impact of the fly ash without estimating the impact of the radionuclides already present before the emplacement of the fly ash (i.e. the “background”). Some other reasons for using linear models are that their mathematical solution is usually straightforward, and they are simple to implement and do not require large amounts of input data. In view of the large uncertainties inherent in long-term assessment, there are major benefits gained by using the simplest models that will provide a defensible result.

In emergency situations, the source term and site characteristics may not be known at the time when decisions have to be made on issues such as evacuation of the local population. In this case, the only way to estimate the impact of the release is to measure the total exposure and subtract the contribution from the existing “background” (provided this is known).

If, in any situation (planned, existing or emergency) the source term cannot be determined, this approach is not applicable, and the impact has to be determined by subtracting the background contribution from the total exposure.

7.1 Continuous discharge problems

So far, the discussion has involved operational (planned) and existing situations in which the contamination is in place and relatively static when assessment is required, or emergency situations where the release of contaminants is of relatively short duration. For situations where contaminants are being continuously discharged to the environment (e.g. from a smelter or power station stack), the same arguments regarding assessment of the impact of “background” apply, provided the assessment models are linear.

8 Stakeholder involvement

The operator and the regulator should be aware of the current and potential problems associated with an operational or existing site. However, it is extremely important to keep all other stakeholders fully informed of any issues that may require attention. This applies to the public in particular, because lifestyles, employment, etc, can be affected by political, regulatory and management decisions, and expensive litigation can be avoided or mitigated by open communication.

9 The future

To this point, this paper has dealt mostly with the current approaches to the management of operational and legacy exposure situations due to NORM and natural radiation. However, this is an evolving field and there are many challenges for the future. These challenges will involve politicians, regulators, the public, the radiation protection community and the broader scientific community.

9.1 Sustainability

There is growing world-wide pressure for development of sustainable approaches to the management of natural resources. In particular land is a valuable resource, both for food production and living space. This implies that any approach to management of operational and existing situations for NORM, where large volumes of material are involved and large areas of land are potentially required for management/disposal of these materials, should solve today’s problems without creating more problems for the future. In operational sites must be managed in such a way that they do not become legacy sites in the future, possibly suing up large areas of land and requiring costly remediation.

9.2 Radiation protection challenges

A major challenge for the RP community is the education of all sectors of the community, with strong emphasis on raising awareness of potential radiation issues without causing unnecessary concern.

There also needs to be a systematic, transparent, robust and cost-effective approach to risk assessment and risk management for today’s legacy sites and existing situations. This will help to develop and establish cost-effective regulatory procedures that will limit the future occurrence of legacy sites and existing situations. This could be done for currently operating sites by allowing release of a site from regulatory control only after the operator has demonstrated to the satisfaction of the regulator that the site is highly unlikely to require any form of active control after release. This is an application of the IAEA concepts of clearance and exemption (IAEA 1996).

Another major challenge will be to find ways of adapting the current approach (based on concepts such as exclusion, exemption, clearance, NORM, graded approach) to the new approach of planned, existing and emergency exposures and the revised Basic Safety Standards (IAEA 2011).

9.3 Scientific challenges

One significant challenge for scientists is to improve their understanding of environmental processes (physical, chemical and biological), and the short- and long-term impacts of contaminant releases, particularly for low-exposure levels, on humans and non-human biota (habitat, lifestyle, viability of species, etc).

Scientists can also make significant contributions to the development of robust methodologies, models and modelling tools to facilitate environmental assessment and remediation (where necessary). This should include development of robust criteria for data acquisition. Two assessment tools that have been successfully applied to a wide range of problems are the RESRAD suite of codes (ANLEAD 1997) and the PC-CREAM suite (Smith and Simmonds 2009). The IAEA VAMP, BIOMASS, BIOMOVS (I and II) and EMRAS (I and II) programs have also contributed significantly in this area.

The role of scientists in education is critically important, particularly in dealing with perception issues. Provision of clear advice, underpinned by good science, is an excellent way of dispelling illusions, and should be applied as often as possible to the process of educating all sectors of the community about the real (rather than perceived) risks associated with exposure to ionizing radiation.

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Appendix

Since the processes involved in this type of problem (environmental transfer, radioactive decay) are irreversible, the assessment model can be described by an equation of the form $\frac{dC}{dt} = AC$ where C is a vector containing the values of the radionuclide concentrations at different points in the region under consideration, and A is a “transfer” matrix, which contains the transfer parameters for the contaminated area (the source) and the surrounding environment.

Since $C = X + B$, where B is the vector of radionuclide concentrations before the fly ash is emplaced (assumed constant), and X is the incremental change due to the fly ash, then

$$\frac{d(X+B)}{dt} = A(X+B)$$

If A is independent of C and t this equation is linear and can be written as (Haberman 1987)

$$\frac{dX}{dt} + \frac{dB}{dt} = AX + AB$$

Before the fly ash is emplaced (i.e. X=0), $\frac{dB}{dt} = AB$.

Therefore, since addition of the fly ash the does not affect the radionuclides already present,

$$\frac{dX}{dt} = AX$$

This means that the impact of the fly ash can be assessed (using a linear model) without needing to consider the impact of the radionulcides present before the emplacement of the fly ash.

In planned and existing situations the source term *X(t=0)*, and the site characteristics (contained in the matrix A), can be determined.