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Radiological protection in Surface and Near-Surface Disposal of Solid Radioactive Waste

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RADIOLOGICAL PROTECTION IN SURFACE AND NEAR-SURFACE DISPOSAL OF SOLID RADIOACTIVE WASTE

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Abstract– This publication provides an update of the recommendations of the International Commission on Radiological Protection for the application of the fundamental radiological protection principles for the disposal of radioactive waste in a surface and near-surface disposal facility. The goal of a surface or near-surface disposal system is to provide protection of humans and the environment from the hazards of radiation. The application of the radiological protection system for a surface and near-surface disposal facility includes the justification of the practice generating the waste and is considered in the context of a planned exposure situation. The design basis for the facility considers the potential for exposures to humans and the environment associated with its expected evolution. Optimisation of protection is an iterative, systematic, and transparent evaluation of protective options for reducing impacts to humans and the environment. Optimisation is essential throughout all life phases and is of particular importance in the design phase, as this will determine the performance of the facility in the operational and post-closure phases. To deal with the far future and low probabilities scenarios optimisation has to be complemented by aspects such as robustness, defence in depth, etc., to provide assurance that reasonable steps have been taken to maintain the long-term integrity of the facility. In case of severe natural disruptive events or human intrusion beyond the design basis, the application of the radiological protection system has to be considered with reference to emergency and/or existing exposure situations. Due to the nature of the hazards and associated timescales, the fundamental strategy adopted for the disposal of low- and very-low-level radioactive waste is to: contain and isolate the waste until the short-lived radionuclides have decayed to levels that can no longer give rise to significant exposures; and limit the activity content of longer-lived radionuclides to ensure that doses and risk are also limited in the long-term, when containment and isolation capacities may be diminishing. The successful implementation of this strategy is demonstrated through a structured safety case. The specific options for a surface and near-surface disposal facility will depend upon the particular situation, including the nature of the waste, the local physical environment and the societal context. Dialogue between the operator, regulator, and stakeholders should be established as early as possible in the process with the inclusion of ethical values to help contribute to promoting a shared understanding of the application of the radiological protection system.

Keywords: Surface disposal; Near surface disposal; Radioactive waste; Ethical values; Life cycle; Design basis

MAIN POINTS

- **The system of radiological protection is applied to the near-surface disposal of solid radioactive waste in the context of a planned exposure situation with appropriate considerations of the timeframes and related uncertainties. Possible exposures to humans and the environment associated with the expected evolution of the near-surface disposal facility included in the design basis, are considered as planned exposure situation.**

- **Optimisation of radiological protection is essential throughout all life phases of a near-surface disposal facility and is of particular importance in the design phase as this will determine the performance of the facility in the operational and post-closure phases.**

- **Optimisation of protection when applied to the development and implementation of a near-surface disposal system, has to be understood in the broadest sense as an iterative, systematic, and transparent evaluation of protective options for reducing impacts to humans and the environment.**

- **Appropriate mechanisms for formal and structured dialogue between the regulator and operator and with stakeholders should be established as early as possible in the process. The inclusion of ethical values in the dialogue is important and can be a useful at promoting a shared understanding.**

- **The uncertainties associated with future exposures must consider both the magnitude and the likelihood of occurrence. Scenarios involving human intrusion require special consideration.**

1. INTRODUCTION

1.1. Background

(1) This report is written as a standalone presentation of how the 2007 ICRP system of radiological protection (ICRP, 2007) and subsequent guidance (ICRP, 2013, 2014a, 2018) should be applied to surface and near-surface disposal of solid radioactive waste. For simplicity this report uses the term "near-surface" to include facilities both on the surface and those somewhat below grade, but near the surface, with the essential feature that the facility is in the biosphere. It supersedes previous guidance on the topic (i.e. ICRP, 1985, 1997, 1998). It covers all issues related to radiological protection of humans and the environment during and following the near-surface disposal of solid radioactive waste, including the post-closure phase. Although this report deals specifically with near-surface disposal of radioactive waste, many of the recommendations may influence the type of waste that can be disposed of at or near the surface and the decision making regarding its management before disposal.

(2) In the context of the Commission's recommendations, residual materials are designated as radioactive waste that need disposal when these materials cannot be recycled, reused or cleared from further control. Radioactive waste contains radioactive substances of a nature and at levels that require appropriate consideration of radiological protection of people and the environment during its management. The final management solution for radioactive waste is disposal, meaning the emplacement of waste in a disposal facility without the intention of retrieval, although retrieval is not precluded. Storage, as opposed to disposal, is considered to be the temporary holding of waste in a storage facility with the express intention of retrieval at a later stage for transport to, and emplacement in, a disposal facility.

(3) Waste management means the whole sequence of operations starting with the generation of waste and ending with the withdrawal of regulatory control following authorized discharge, clearance or disposal of solid waste and is normally undertaken within the framework of a national policy and strategy. Figure 1 provides an illustration of the overall radioactive waste management path from the generation to the disposal of waste (NEA/RWM, 2016). The whole system providing radiological protection for the waste management process needs to be optimized, not just the disposal facility. On this point, the disposal facility is the technical installation with all its physical components, in essence what is operated. The disposal system is conceptually broader and is the combination of the waste emplaced, the engineered barriers and the geology/environment, as they assure together the protection level required. This is important because it is all those components together that assure the protection. Optimisation should extend to considering each step of waste management such as processing and storage, transportation, and disposal options along with broader considerations such as centralised versus decentralised approaches (e.g. use of a common regional or national facility servicing many sources of waste or specific facilities for each source of waste).

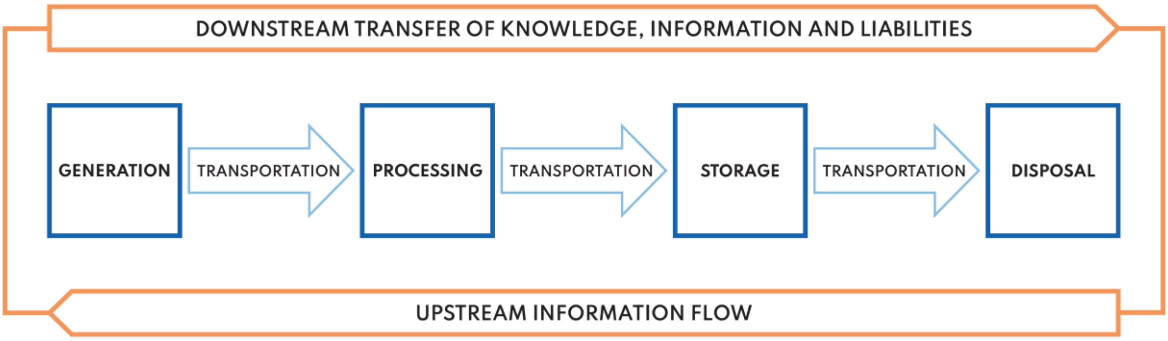

Fig. 1. Schematic of Radioactive Waste Management Path.

(4) Management of radioactive waste involves a number of interdependent steps and activities and communication between different responsible parties and other stakeholders is an important part of this process. Equally important is the transfer of information and experience in both directions. Actions taken before disposal can influence the disposal options. This is particularly true for waste potentially suitable for near-surface disposal, considering the variety of activities that generate waste that may be destined for such facilities. Initially the radioactive waste is collected and characterised, then processed as part of predisposal management. Processing of waste is generally undertaken to reduce its volume and/or to convert it to an inert and chemically stable form. Waste is often stored both during and between the different management steps, the period of storage can be relatively short or can last for several decades.

(5) Storage of radioactive waste with half-lives in the range from a few days to a few years can be useful to enable the radionuclide content to decay to the extent that the waste can be cleared from further radiological protection control measures. Storage may also be necessary if suitable disposal facilities are not available, however, it is an interim step in radioactive waste management, with authorized discharge, clearance or disposal being the endpoint. Prolonged storage may eventually create safety and security concerns, as well as demand for resources that could be better spent on safe disposal. Hence, policies governing radioactive waste management need to include plans for timely disposal.

(6) All exposure situations (i.e. planned, existing, and emergency exposure situations) offer the prospect that waste may be generated. The ICRP system of radiological protection would be applied in the context of the prevailing exposure situation in which the waste is being generated. Nonetheless, the Commission recommends that the management of a near-surface disposal facility largely follow the same principles and practices as those applicable for a planned exposure situation.

(7) The application of the system of radiological protection for near-surface disposal of solid radioactive waste needs to be done with appropriate considerations of timeframes and uncertainties. Estimates of dose and risk to individuals and populations, as well as the environment, will be subject to a range of uncertainties as a function of time, associated with future disposal facility evolution, surrounding environmental conditions, climate, social and economic conditions, and human habits and characteristics. Furthermore, due to the time scales involved, verification that protection is being achieved cannot be carried out in the same manner as for an operating facility (e.g. for routine discharges from operating facilities). Additionally, it should be noted that while a disposal facility will continue to fulfil safety functions after its closure, it cannot definitively be assumed that effective mitigation measures will necessarily continue, should they be required in the future. In view of the

uncertainty over the evolution of the facility and possible radiological impact, some aspects of the consequences in the future are viewed from the perspective of a potential exposure.

(8) This report is focused on the ICRP system of radiological protection, which underpins the international framework for safety, using terminology and concepts that are compatible with that framework. In order to foster coherence with the international framework for safety the report uses terminology and concepts that are consistent with that espoused in the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (IAEA, 1997) as well as the Safety Standards of the International Atomic Energy Agency (IAEA, 2006).

1.2. Scope

(9) This report deals with the radiological protection of people and the environment in accordance with the ICRP system of radiological protection outlined in *Publication 103* (ICRP, 2007), in the context of the disposal of solid radioactive waste in near-surface disposal facilities. The recommendations given in this report apply to the design, construction, operational, closure and post-closure phases of disposal facilities. They apply to planned facilities and to the transitioning from one phase to the next, but can also be applied retrospectively, i.e. to currently operating or closed facilities under institutional control. They should be taken into account in the justification of practices generating waste and in the development of the national radioactive waste management policy and associated strategies.

(10) This report focuses on the radiological protection issues associated with the disposal facility. It does not consider predisposal management, including transportation and storage. Similarly, specific guidance on siting is not provided, although its importance for the protective capability of the facility is acknowledged and the recommendations of this report may influence site selection.

(11) This report considers some aspects of the safety case and provides a description of how the system of radiological protection can inform the development of the safety case (Section 4). A safety case is a structured set of arguments and evidence demonstrating that specific targets and criteria are met, during facility design, construction, operation, closure and in the post closure period of a near-surface disposal facility. However, the overall safety of the facility depends on a wide range of issues and characteristics, including non-radiological aspects of its siting, design and operation. An integrated approach to all aspects of safety is recommended.

1.3. Structure

(12) Section 2 provides an overview of key radiological protection considerations in near-surface disposal of radioactive waste. Section 3 describes the Commission's system of radiological protection as it applies to the near-surface disposal of radioactive waste, including the ethical considerations, exposure situations, and the applications of the basic principles of the system of radiological protection with an emphasis on optimisation. Section 4 provides guidance on the implementation of the system of radiological protection at the various phases of the near-surface radioactive waste disposal facility. Conclusions are provided in Section 5.

2. OVERVIEW OF RADIOACTIVE WASTE AND NEAR-SURFACE DISPOSAL

2.1. Generalities

(13) Radioactive waste arises from a wide range of activities such as the use of radionuclides in hospitals and research laboratories; the use of radioactive materials in industrial processes; the production of electricity by nuclear power, operation of research reactors, radioisotope production, dismantling and decommissioning of nuclear facilities, decontamination activities from nuclear accidents, remediation activities from past practices and mining and minerals processing operations and other industrial processes. Considerable amounts of radioactive waste have also been generated by military programmes.

(14) Radioactive waste has a wide variety of characteristics and precise classification schemes vary between different regulatory regimes. The IAEA document Classification of Radioactive Waste General Safety Guide No. GSG-1 (IAEA, 2009) provides a useful scheme that has six classes of waste from Exempt Waste (below concern from the radiological protection perspective) to High-Level Waste. These six classes of waste have broad ranges of characteristics that help determine generic disposal options, as illustrated in Figure 2. Within this scheme the waste types most appropriate for near-surface disposal are low-level waste and very-low-level waste.

(15) Low-level waste is that which is considered suitable for near-surface disposal and can have a range of activity concentrations from just above very-low-level waste to levels that require shielding and more robust containment and isolation for periods up to several hundred years (IAEA, 2009). Similar to facilities for very-low-level waste, the range of design options for near-surface disposal facilities varies from simple to more complex ones and may involve disposal from the surface to depths of several tens of metres. This depth range is not indicative only and is not precise. Some types of waste that would be considered Intermediate Level Waste in other locations or for other disposal facility designs may be appropriate for near-surface disposal in specific circumstances. A number of factors including the limits on the concentrations of long-lived radionuclides, use of engineered barriers, and depth of disposal all need to be considered in the design of a facility.

(16) In addition to the volume and activity of the waste, the physical and chemical properties are important when assessing and selecting management and disposal options for different forms of waste. Examples of waste types include disused sealed sources, consumables (e.g. paper, swipes, laboratory solid waste, etc.), filter media, activated components, and diffuse waste, such as remediation waste and tailings. As part of developing a near-surface disposal facility, it may be possible to use processing options to modify the waste form to be more conducive to the expected long-term performance of the disposal facility.

(17) From a radiological protection point of view, the radionuclides of primary importance can be different between the operational phase of the disposal facility and its post-closure phase. Short-lived radionuclides, which for purposes of waste disposal are generally considered to be radionuclides with less than a 30-year half-life, are expected to be isolated and contained from the environment while they decay sufficiently, however, many radionuclides in this category are of primary importance to worker protection, particularly those that emit gamma radiation. Conversely, long-lived radionuclides, those with a half-life greater than 30 years that are weak-beta or alpha emitters, can still be a hazard in the long

term, but generally do not represent a significant hazard during the operational phase, as the waste is generally handled such that the potential for ingestion and inhalation are minimized. In other situations, the same long-lived radionuclides maybe a concern for both the operational phase and long-term safety of the facility, for example, radium-226 is a gamma emitter and has a 1600-year half-life. The key point is the safety assessment needs to consider all phases of the disposal facility and the various potential exposure pathways.

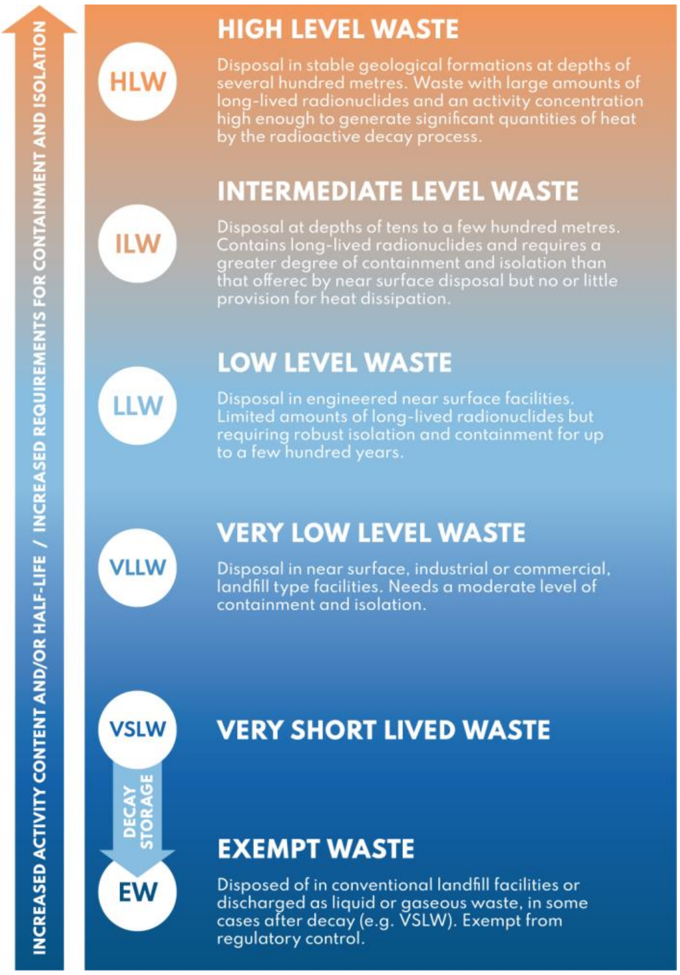

Fig. 2. Stylized Representation of IAEA Classification of Radioactive Waste[1].

(18) In summary, the principal characteristics of waste that influence its management are volume, chemical and physical form, and radionuclide content. These characteristics vary over a very-wide range, depending on the process from which the waste originates and the radionuclides involved. A variety of management and disposal options may, therefore, be appropriate, depending on the characteristics of the waste.

[1] Note that the term ‘activity content’ is used because of the generally heterogeneous nature of radioactive waste; it is a generic term that covers activity concentration, specific activity and total activity (IAEA, 2009).

2.2. Management options for the near-surface disposal of radioactive waste

(19) It is internationally recognised that there is no implied intention to retrieve disposed waste even if technical options to do so were available. The disposal options considered for different types of waste aim to provide increasing levels of containment and isolation for waste of higher activity and/or longer-lived radionuclides. Currently the commonly adopted option is to dispose of short-lived and limited concentration of long-lived low, and/or very-low-level radioactive waste in near-surface disposal facilities designed for those waste types.

(20) The goal of a near-surface disposal system is to provide protection of humans and the environment from the hazards of radiation. Due to the nature of the hazards and associated timescales, the fundamental strategy adopted for the disposal of low- and very-low-level radioactive waste is to contain and isolate the waste until the short-lived radionuclides have decayed to levels that can no longer give rise to significant exposures, and to limit the activity content of longer-lived radionuclides to ensure that doses and risk are also limited in the long-term, when containment and isolation capacities of the disposal facility may be diminishing. In addition, consideration needs to be given to protection from the possible impacts from non-radiological contaminants. The implementation of this strategy is demonstrated through a structured safety case.

(21) Access, whether deliberately or inadvertently, to waste in a closed near-surface facility is easier compared to waste disposed in a geological disposal facility. Consideration should be given to different approaches to reduce the possibility and consequences of post-closure inadvertent human intrusion through site selection, design, management, and institutional oversight and control.

(22) The current generation of people who dispose of the waste have an ethical obligation to protect the environment and future generations, taking into consideration current cultural sensitivities and their potential future significance when developing national waste management strategy. This should address the possibility of no control being in place over the facility in the future.

(23) Disposal facility siting and design options for radioactive waste are selected to provide containment of the waste within the facility and isolation from people and the environment. Disposal facility designs also consider disruptive processes and events. The degree and extent of containment and isolation needed are dependent on the potential hazard posed by the waste (i.e. radionuclide content and its chemical and physical form).

(24) Near-surface disposal facilities are intended to provide the degree of containment and isolation needed for solid low- or very-low-level radioactive waste, which can contain both short-lived and long-lived radionuclides. For the short-lived radionuclides, this will be a period of several hundred years. Radioactive decay, particularly of short-lived radionuclides, causes the hazard to change over time. The hazard of inadvertent human intrusion into waste that contains mainly short-lived radionuclides would reduce significantly during the period of a few decades to a few centuries following closure. For longer-lived radionuclides, including some naturally occurring radionuclides, the necessary period of containment will be longer, hence the need to limit the activity content of long-lived radionuclides in the waste disposed of in near-surface facilities. Containment and isolation are provided physical barriers and to help ensure their ongoing integrity measures such as institutional control to access of the disposal site and restrictions on the use of the land associated with the site are important. Site selection should take into account the likelihood of severely disruptive events. The likelihood of deterioration of the barriers caused by deliberate human actions can be reduced by avoiding, to the extent possible, locations with valuable underground mineral, water and other resources.

(25) The type of disposal that is appropriate for a particular waste type depends on the degree and duration of containment and isolation required to achieve the desired level of protection. The degree of engineering for any approach is influenced by the local climate, the site characteristics, and the nature of the waste. The range of potential disposal options are described below:

a. Landfill sites may be suitable for some very low-level waste. The duration of control of sites is generally short, and waste cannot be assumed to be isolated from the environment for more than a few tens of years.
b. Disposal by leaving waste in situ, e.g., foundations of decommissioned buildings.
c. Surface trench disposal on designated sites is used for large volumes of low-level waste.
d. Near- or on-surface engineered facilities such as vaults or boreholes to depths down to a few tens of metres are used for low-level waste.
e. Tailing dam facilities and open pit mines are used for uranium and NORM mining tailings.
f. Underground caverns and mines are used for large volumes of low-level waste and provide possibilities for intermediate-level waste.
g. Disposal in stable geological formations a few hundred metres below the surface is the option currently adopted for high-level radioactive waste and is also suitable for intermediate-level waste. Recommendations for radiological protection considerations for deep geological disposal are provided in *Publication 122* (ICRP, 2013).

(26) A key concept in the disposal of radioactive waste is containment, which is the confinement of the radionuclides within the engineered barriers that either constitute the waste form or the engineered features of the disposal facility, together with the natural features that separate the waste from the accessible biosphere. Isolation relies on placing a separation between the waste on the one hand and people and the environment on the other. It also means design to minimize the influence of factors that could reduce the integrity of the disposal facility. Whereas, confinement relies on engineered barriers to ensure the necessary level of containment for a predefined period, as well as on engineered and natural barriers after this period, in order to limit the release of radionuclides to the environment and to delay it in time (retardation). In the case of deep geological disposal, isolation can be provided by disposal in a stable geologic formation at an appropriate depth providing clear physical separation of the waste from the surrounding biosphere and creating protective conditions for the containment barriers of the disposal system. In contrast to high-level waste, some waste classes (e.g. very-low- and low-level waste with limited content in long-lived radionuclides) can be disposed of at the surface or near the surface in the accessible biosphere. In this case, protective actions (e.g. access control, land use control) are needed to provide isolation for a time period (e.g. several hundreds of years) in accordance with the waste related hazards. These concepts are illustrated in Figure 3.

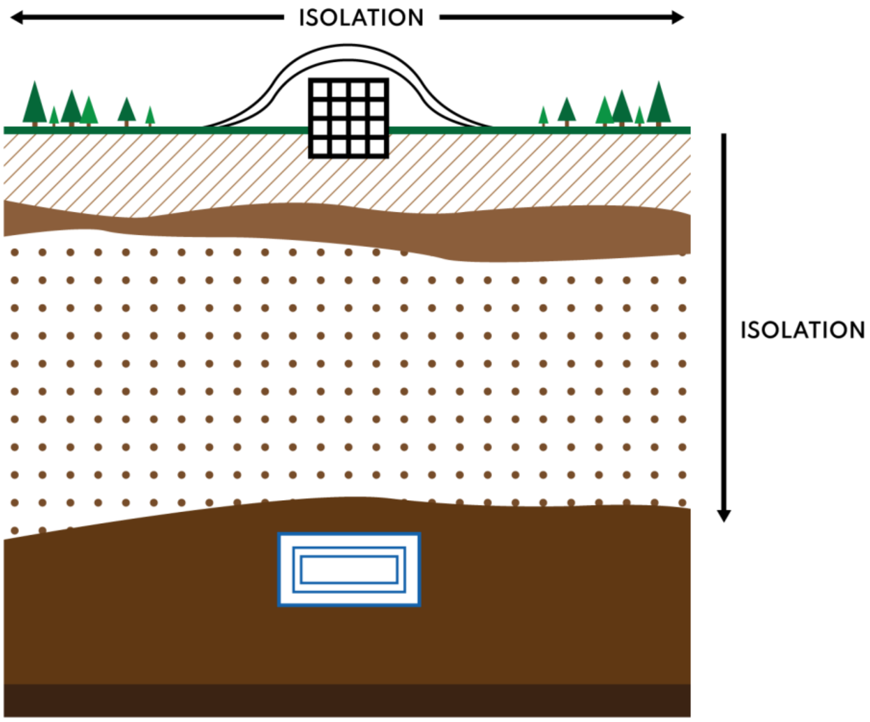

Fig. 3. Isolation with near-surface disposal and deep geological disposal.

(27) A safety case must demonstrate the suitability of the disposal facility (the site and engineering) for the waste intended to be disposed. The goal of containment and isolation is to provide protection for as long as necessary, while acknowledging that some dispersion of radionuclides in the environment may occur over the long term resulting in some exposures.

(28) A wide variety of extractive industries and subsequent processing activities deal with NORM and generate waste with a large range of physical, chemical, and radioactive properties. While it is common for the raw material to contain low concentrations of long-lived radionuclides (e.g. natural uranium and thorium and their decay series, potassium-40), subsequent processing can separate and concentrate radionuclides in the decay series in different waste and product streams. Some of these processes give rise to large volume waste streams with relatively low concentrations of radioactivity, but with long radioactive half-lives. In addition, such waste typically has other contaminants (e.g. heavy metals). The radioactive properties may be a minor and even insignificant consideration from the overall protection perspective for both humans and the environment and therefore an integrated approach is recommended, taking all hazards into account, when deciding on a management strategy for NORM, including disposal of NORM waste. The Commission's recommendations for radiological protection in management for industrial processes dealing with NORM are outlined in *Publication 142* (ICRP, 2019).

(29) Because of the large waste volumes, the waste from mining and milling operations is often disposed on the mine site or at the site of a common processing facility. In some cases, mine residues may be produced that can be recycled and reused and this can reduce waste volumes. However, eventually waste material will be produced and its proper disposal needs to be considered in the planning stages. The optimisation considerations should include the possibility of the waste to be returned to the mine (underground or open pit) from which it was extracted.

(30) The fact that the potential hazards from the long-lived radionuclides and other associated non-radioactive contaminants persist well beyond the lifetimes of engineered structures results in specific challenges to keep the waste away from humans and the environment, and the need exists for some form of ongoing control. A related issue of concern is the potential use of some mining and minerals processing waste for landfill or construction material, and the nature of institutional control exercised over such waste to prevent diversion and inadvertent human intrusion should be duly considered.

(31) The issue of radon is broader than waste disposal and the ICRP recommends that radon should be managed in accordance with the approach of *Publication 126* (ICRP, 2014b). Depending on the nature of the material, exposures to radon (Rn-222 and Rn-220) emanating from the waste may need to be given careful consideration in the safety assessment of near-surface disposal facilities for such waste. This may be particularly relevant for the management and disposal of NORM waste (ICRP, 2019). As described in *Publication 126* (ICRP, 2014b), the Commission recommends that the management of radon exposures should be mainly based on application of the optimisation principle using a reference level, translated for practical reasons to concentrations in air, to facilitate implementation. If radon mitigation actions cannot reduce levels to less than the reference level, the exposure will need to be considered as part of the occupational exposure. For some near-surface disposal facilities (e.g. uranium tailings) the exposure of workers to radon is not incidental, but a reasonably expected part of the operation of the facility, and in this situation they would be considered occupationally exposed. The occupational dose limits should apply when the national authorities consider that the radon exposures should be managed as a planned exposure situation.

2.3. Phases of a near-surface disposal facility

(32) Figure 4 provides a summary of the phases of a near-surface disposal facility and some of the associated radiological issues. The lifecycle of the disposal facility has been divided into three general categories: pre-operational, operational, and post-closure. The upper half of the figure describes the general activities occurring at a site and the relative span of time that activity could occur along with associated key decision points for these activities. For example, siting occurs early in the pre-operational phase, while design can start during the siting evaluation and continue throughout the operational life of the facility. It shows that design, construction of new disposal units, emplacement in built units and closure of full units can be occurring at the same time across a single disposal facility. The figure also demonstrates that after closure, activities are expected to be limited to those included in the planned institutional oversight and controls for the site. For example, a period of continued regulatory control, monitoring of the cover, land use restrictions, preservation of land use records, monitoring by society to check that the conditions are not degrading. The lower half of the figure indicates general radiation protection activities occurring in the three time periods. The figure highlights that environmental monitoring starts before the disposal facility is built to understand the nominal background levels and continues far into the post closure. Worker protection is shown fading in the post closure as active measures are curtailed and while maintenance may still be performed, potential doses should not require radiation workers.

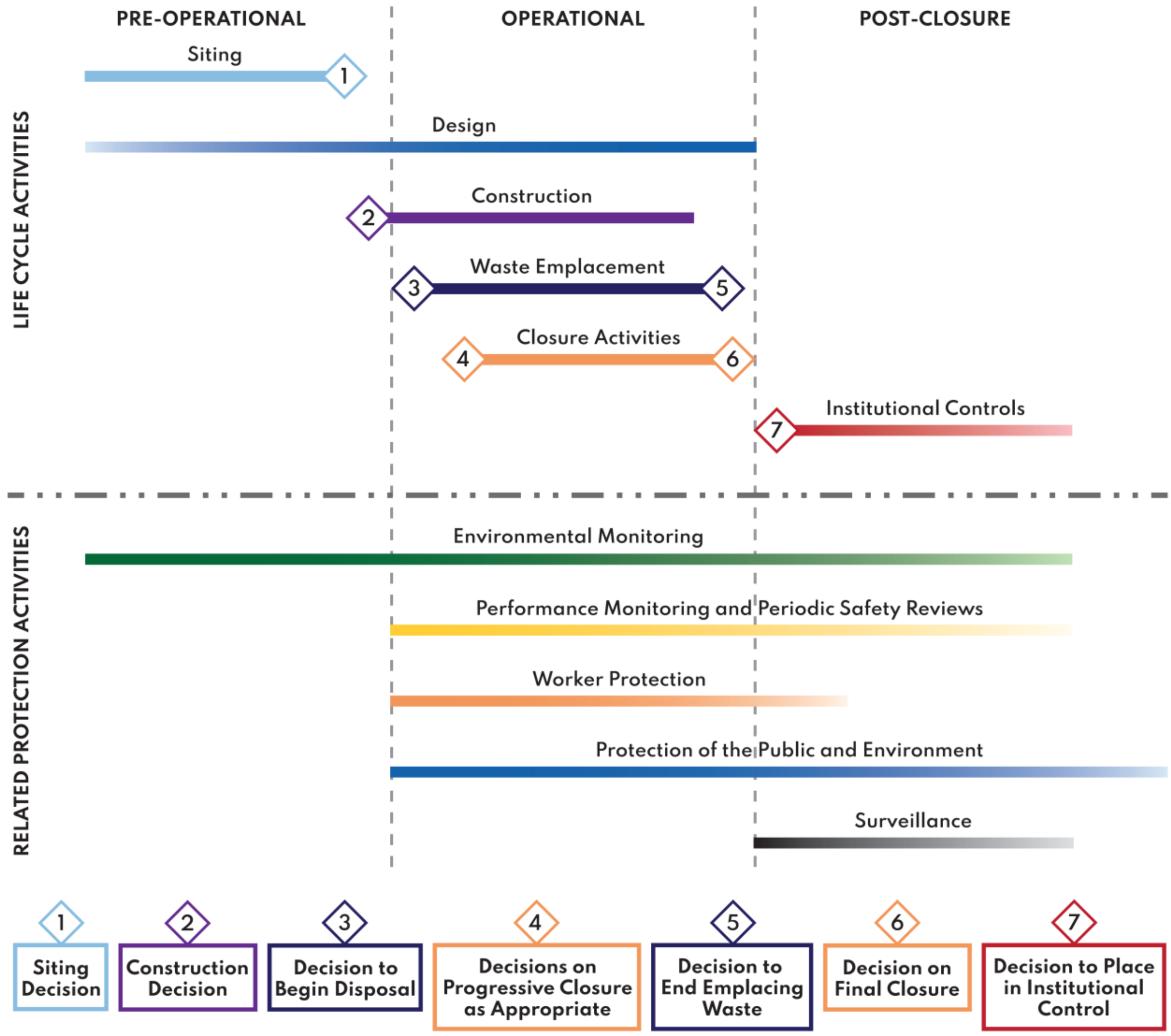

Fig. 4. High-level overview of the life cycle of near-surface disposal facility.

3. THE APPLICATION OF THE SYSTEM OF THE RADIOLOGICAL PROTECTION TO NEAR-SURFACE DISPOSAL OF RADIOACTIVE WASTE

3.1. Principles of the RP system and ethical considerations

(33) The system of radiological protection, as described in the 2007 Recommendations (ICRP, 2007), continues to rely on three fundamental principles: justification, optimisation of protection and application of dose limits. Justification and optimisation are applied to the three types of exposure situations considered by the Commission to organize radiological protection: planned exposure situations, emergency exposure situations and existing exposure situations, and dose limits are applied in planned exposure situations other than medical exposures.

(34) It should be noted that waste can come from all types of exposure situations and once the decision of implementing a near-surface disposal facility is taken the logical steps and behaviours are best described as a planned exposure situation. While most circumstances will be relatively straightforward examples of planned exposure situations (e.g. disposal of radioactive waste from the operation of a nuclear facility), others from different exposure situations maybe more nuanced (e.g. dealing with waste in a contaminated territory with a near-surface disposal facility as part of an existing exposure system). The disposal of waste is an example showing that the situation-based approach provides a way to organise thinking and not to create rigid boundaries in terms of exposure situations. The goal is to provide optimal levels of radiological protection suitable to the prevailing circumstances. For example, a near-surface disposal facility within the context of an existing exposure situation will need to ensure protection of workers during the operational phase and, similar to the situation with radon exposures, the national authority could apply the occupational dose limits and other aspects of a planned exposure situation. The involvement of stakeholders will be critical in deciding upon the appropriate controls and criteria for the specific circumstances.

(35) The system of radiological protection has a strong ethical foundation. The Commission has elaborated on the ethical foundation in *Publication 138* (ICRP, 2018), with particular attention given to four core ethical values, namely: beneficence/non-maleficence, prudence, justice and dignity.

- Beneficence/non-maleficence: promoting or doing good and avoiding doing harm. This is reflected, for example, in the primary aim of the system of radiological protection of an appropriate level of protection without unduly limiting desirable human actions.

- Prudence: making informed and carefully considered choices without full knowledge of the scope and consequences of an action. Prudence is reflected, for example, in the consideration of uncertainty of radiation risks for both humans and the environment.

- Justice: fairness in the distribution of advantages and disadvantages. Justice is a key value underlying, for example, individual dose restrictions that aim to prevent any individual from receiving an unfair burden of risk or costs.

- Dignity: the unconditional respect that every person deserves, irrespective of personal attributes or circumstances. Personal autonomy is a corollary of human dignity. This underlies, for example, the importance placed on stakeholder participation and the empowerment of individuals to make their informed decisions.

(36) These core ethical values underlie the three main principles of radiological protection: justification, optimisation and dose limitation. Applying the principles of radiological protection requires that radioactive waste disposal solutions adopted should result in doing more good than harm (beneficence/non-maleficence), unnecessary risk being avoided (prudence), avoiding unfair distribution of risk (justice) and people being treated with respect (dignity). In addition, supporting the application of these core ethical values the system of protection also relies on procedural ethical values namely: accountability, transparency and inclusiveness (ICRP, 2018).

(37) This ethical framework offers another lens to assess a situation beyond the technical options and in some instances could be the discriminating factors in choosing a course of action. For example, where there are several options that are in principle technically acceptable, it is possible to evaluate which is more prudent or which better ensures the dignity of individuals involved. While the system of radiological protection is concerned with ensuring adequate protection of people and the environment, the ethical values could guide considerations of how protection is best achieved while being mindful of possible unintended consequences.

(38) The Commission considers that radioactive waste management is an integral part of the practice generating the waste; it is not a free-standing practice that needs its own justification. Therefore, justification of the practice generating the waste includes the management options for the waste including its disposal. In addition, this evaluation needs to extend to the environment. If the management of waste was not considered in the justification of the practice generating the waste and/or the practice in question is no longer in operation, the Commission recommends that the protection of humans and the environment should be optimised irrespective of any justification of such past practice. The overall goal is to ensure the well-being of individuals and the quality of the living in general. As already noted, this principle has a clear link to the ethical value of beneficence/non-maleficence and the assessment process needs to consider a broad view of human health and other hazards besides radiation.

(39) The importance of the optimisation principle was reinforced in the 2007 Recommendations (ICRP, 2007). For this purpose, ICRP recommends that in assessing the level of protection for humans: ‘the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors’ (ICRP, 2007, Para. 203). The optimisation process also needs to consider environmental exposures for the purposes of environmental protection (ICRP, 2014a). To ensure that a near-surface disposal system provides the required level of radiological protection, in addition to the dose calculations, the assessment needs to consider its site and engineered features, such as robustness, best available techniques (BAT), safety margins, and defence in depth.

(40) The optimisation process has a number of ethical dimensions. Balancing the many factors necessary to optimise the radiological protection of the facility requires (prudent) decisions to be made, sometimes with incomplete knowledge. For example, there will be considerable uncertainty in potential changes to the climatic environment and the geomorphological evolution of the surrounding environment over the long term and these and other uncertainties will need to be factored into the design of the facility. Prudence is required to ensure we do not unduly burden either the current or future generations with our decisions regarding disposal. This naturally raises the issue of justice and in particular distributive justice and also the dignity of the current and future generations.

(41) Distributive justice has two relevant dimensions, namely spatial (amongst present populations) and temporal (between present and future generations). Spatial distributive justice concerns the distribution of advantages and disadvantages among different groups of people, either nationally or internationally. This should also include the financial burden with respect to waste disposal facilities. The group of people who have enjoyed the benefits of the waste producing activity are not necessarily the ones who are faced with the potential burdens of managing the radioactive waste. Temporal distributive justice, also referred to as intergenerational justice, requires the health and wellbeing of future generations to be protected. These justice considerations should be addressed by near-surface disposal facilities being designed and operated in a way that they provide a high-level of assurance along with adequate protection to both present and future generations and the environment.

(42) The principle of dose limitation can be linked to the ethical value of dignity. Dignity concerns the unconditional respect that each individual deserves, regardless of age, sex, health, social condition, ethnic origin and religion. As such, it emphasises the promotion of autonomy for those exposed to radiation including both radiation workers and the members of the public. In the context of waste disposal, dignity also emphasizes that belonging to a generation that happens to come later in time is not sufficient reason for a different treatment. The application of dose limitation puts bounds on the risks deemed acceptable to individuals, regardless of optimisation or other considerations, and requires that each individual be considered. The principle of dose limitation has a role to play in radioactive waste disposal as it is considered a planned exposure situation and hence, the Commission recommends the use of dose limits. This is straightforward in the operational phase of the facility. However, it is recognised that the calculated doses for public exposure in the far future are rarely the dominating factor in assessing various disposal options, particularly when the differences between the doses are small. Additional information to the decision-making process can be obtained by assessing the probability of disruptive events (e.g. earthquakes, flooding etc). Beyond the dose limits, the control of public exposure will be achieved through a process of constrained optimisation such that controls necessary to ensure the long-term proper functioning of the facility are identified and properly designed, constructed and operated.

(43) It is not only important to consider the outcomes of the application of the radiological protection principles from an ethical point of view, but also how these processes are being conducted. The three procedural values underlying the system are mutually reinforcing and together they allow stakeholders to be aware of up-to-date information required to effectively participate in decision making processes related to the facility. As such, these procedural values become a key part of good governance, via effective regulatory processes and the design thereof, in the management of the facility and provide for an effective and balanced integration of technical and social aspects.

(44) Accountability as a procedural ethical value emphasizes that people who are in charge of decision-making must answer for their actions to all those who are likely to be affected by these actions including reporting on their activities, accepting responsibility, and

to be ready to account for the consequences, if necessary. The Commission also considered the accountability of the present generation to future generations related to waste management and the protection of the environment (ICRP, 1997, 1998, 2003, 2013). Accountability in this context is the implementation of the value of (intergenerational) justice (ICRP, 2018), in that we appropriately take their interests into account while, in doing so, also avoiding unreasonable actions that would be detrimental to today's generations.

(45) An important aspect of the implementation of the value of procedural justice is transparency, which is concerned with the accessibility of information about the deliberations and decisions concerning potential or on-going activities, and the honesty with which this information is transmitted. Transparency enables social oversight and vigilance of the public. This is also emphasised in the need for communication and public involvement, which starts at the planning stage and well before decisions are taken from which there is no return. Transparency and accountability can be mutually reinforcing. Together they allow stakeholders to be aware of up-to-date information required to make informed decisions and also to participate in the decision-making process. There has been general trend to incorporate these two procedural values in consultation processes involving environmental matters and they have become a key part of a good governance policy in organisations (ICRP, 2018).

(46) Inclusiveness, often referred to as stakeholder participation, is the third procedural value, and is the participation of all relevant parties in the decision-making processes related to radiological protection. Good governance requires effective stakeholder participation with a structured, early, and meaningful involvement in decision making processes on radioactive waste management. Within the context of transparency and accountability, effective stakeholder participation is a necessary element to facilitate ethically responsible decisions. Stakeholders include individuals and groups having personal, financial, legal, or other legitimate interests in policy or recommendations directly affecting their well-being or that of the environment for current and future generations. Stakeholders could range from the local to international level.

(47) Both the core values and the procedural values have a bearing on near-surface radioactive waste management and highlight the radiological protection and societal-economic issues associated with the longer-term dimensions of the hazard from radioactive waste. In particular, the disposal of long-lived waste clearly points out the limitations of purely technical solutions to the situation. On the one hand, the current generation has a duty to ensure future generations and the environment are safe from present-day radioactive waste management practices, including disposal, and that they do not have undue burdens placed upon them and the environment to achieve safety. However, it is not possible to envisage how society will be organised in the longer term and distant future. These issues highlight the need to use the ethical values in the development of waste management strategies. In conjunction with the core values, one should strive for respecting the dignity of future people, while – from a perspective of beneficence/non-maleficence – one should not harm their interest. This is done in part by considering the impacts on future generations and balancing them against the current generations and requires considering prudent courses of actions and decisions in near-surface radioactive waste disposal that are protective without being unduly conservative.

(48) The Commission continues to recommend that individuals and populations in the future should be afforded at least the same level of protection as the current generation: doses and risks for member of the public in the long term should not exceed the criteria used in the design stage, taking into account that the assessment of radiological impacts presents a challenge due to uncertainties.

(49) The obligations of the present generation towards the future generation are challenging involving, for instance, not only issues of protection, but also transfer of knowledge and resources. There is no certainty how society will evolve over time and the present generation cannot ensure that in the future society will take any actions related to the safety features of a disposal facility. There will always be a range of possible evolution scenarios for a near-surface disposal facility and no single scenario can be predicted with certainty. In addition, for a near-surface disposal facility the isolation of the waste relies more on human protective actions than geology as is the case for deep geological disposal. This highlights the importance of the transfer of knowledge and resources to future generations to enable them to address protection issues associated with the disposal facility.

3.2. Exposure situations

(50) The 2007 Recommendations organise the system of protection according to three types of exposure situations: planned, existing and emergency exposure situations (ICRP, 2007, Para. 176).

- 'Planned exposure situations' are situations involving the deliberate introduction and operation of sources of exposure. Although the situation is planned by the deliberate introduction of the source of exposure, exposures are not necessarily anticipated or planned to occur. Planned exposure situations may give rise both to exposures that are anticipated to occur (normal exposures) and exposures that could occur but are not expected to occur (potential exposures). Normal exposures are those that are virtually certain to occur and which have a range of magnitude which is predictable, with the attendant uncertainty. Potential exposures refer to situations where exposure could possibly take place e.g. an unexpected evolution or accident, but no certainty that it will occur. While normal and potential exposures are issues for near-surface disposal facilities, potential exposures represent a particular challenge.

- 'Emergency exposure situations' are exposure situations resulting from a loss of control of a planned source (e.g. an accident), or from any unexpected situation (e.g. a malevolent event), which require urgent action to avoid or reduce undesirable exposures.

- 'Existing exposure situations' are situations resulting from sources that already exist when a decision to control them is taken (natural radiation, past activities or after emergencies).

(51) The deliberate introduction of the near-surface disposal facility is a planned exposure situation, nevertheless exposures from the facility are not planned to occur as such. The aim is to prevent and reduce exposures to as low as reasonably achievable, taking economic and societal factors into account, both in the operational phase (waste emplacement and closure) and in the post-closure phase when the facility is functioning as a passive system. In the long term, after closure and when oversight of the disposal facility is no longer in place, there is a possibility for exposure to occur because of the anticipated decrease in the level of containment and isolation provided by the disposal system or because of natural disruptive events or inadvertent human intrusion. There is no certainty that such exposure will occur and there will be a range of possible exposures that could occur. Possible exposures could

range from zero to a level that is bounded by the waste and disposal facility characteristics. While the range of doses can be estimated, the actual outcome cannot be predicted and as such, the Commission considers them within the conceptual system of protection as potential exposures. As such, the risk should be considered in terms of both the magnitude and likelihood of occurrence of these exposures.

(52) The design objective for the near-surface disposal system is to ensure that its containment and isolation functions will not be jeopardized by the range of developments that could reasonably be expected to occur during the lifetime of the facility. These functions are mainly ensured by built-in and passive safety features designed to last far beyond the institutional control phase, not requiring any human action. Optimisation should continue after the design phase, up until the complete transfer of the system into a passive state. However, optimisation is crucial at the siting and design phases, which determines the boundaries for the performance of the facility in subsequent phases. Some developments will be certain to occur and others could occur, but with less probability and give rise to exposure. In the optimisation process, conditions, events or processes would normally be excluded from general consideration based on very low probabilities or consequences. These circumstances are usually representative of planned exposures (normal or potential), but an unusual event could lead to less than desirable radiological conditions. In the context of near-surface disposal of radioactive waste, an actual emergency exposure situation is extremely unlikely, but could lead to an existing exposure situation that requires some form of remediation.

(53) For the operational phase of the near-surface disposal facility both normal exposures and potential exposures should be considered, where potential exposures are those related to situations where higher exposures can potentially occur than in normal exposure situations, following deviations from planned operating procedures, accidents including loss of control of radiation sources, and malevolent events. For the post-closure phase of the near-surface disposal facility potential exposures need to be considered.

(54) While emergency exposure situations should be considered, such exposure situations would be expected to be very unlikely and limited in scope for near-surface disposal facilities, because of the strong limitation of activity in the waste disposed and the generally inert and immobile form of the waste. As such, the range of emergency exposure situations that could possibly occur is limited. Only very severe disruptive events during disposal operations could possibly lead to an emergency exposure situation followed by an existing exposure situation; these have to be identified and assessed at the design stage of the facility and to the extent possible designed out or mitigated. After closure of a near-surface disposal facility, the intentionally limited radioactive content of the waste and the slowly evolving containment and isolation of the radioactive waste make the occurrence of emergency exposure situations very unlikely. Only abrupt and severe perturbations of the disposal system that are outside the design basis might possibly lead to an emergency exposure situation.

(55) Near-surface disposal facilities are at various phases of development and operation in several countries: under design, under construction, in operation or closed and under some degree of regulatory control. Disposal facilities in operation or already closed and under direct oversight are considered as situations where the source is under control; these are therefore planned exposure situations. If an operational or closed disposal facility evolves in line with its planned and designed functioning as defined in the safety case, the concept of planned exposure situation continues to apply. While the facility should be designed to protect future generations, these are invariably judged by today's standards and changing societal expectations or priorities may impact how the facility is judged and managed. In addition, there could be a breakdown of controls. Within the context of the current system of radiological protection, which itself may have changed, the situation could be considered as

an existing exposure situation, requiring decisions to be taken, although not necessarily urgently, to bring the facility under control again (e.g. re-establishment of a control regime or retrieval of the waste).

(56) Transcending the particular exposure situations that are deemed to apply during the various stages of the lifecycle of a near-surface disposal facility, the system of protection is implemented by assessment of the situation, justification of taking action, and optimisation of the protection actions using appropriate dose criteria for the individuals impacted.

3.3. Dose and risk concepts

(57) One of the primary uses of effective dose in radiological protection for both occupationally exposed workers and members of the public is for optimisation of protection at the planning and development stage by comparing with dose constraints or reference levels and for the retrospective assessment of dose for demonstrating compliance with dose limits (ICRP, 2007, Para. 153). When assessing the possible exposures arising from a near-surface disposal facility in the distant future, the time frames to be considered are very long and the associated uncertainties in calculation assumptions, (e.g. climatic conditions, release and migration rates, human habits, etc.) give rise to intrinsic difficulties and challenges for compliance demonstration with the system of radiological protection. Achieving protection for a disposal system, including the process of optimisation of protection, requires a broader approach than just the use of dose limits and a purely radiological optimisation process and will need to encompass the management system and quality processes employed for the project. These other factors are important in helping to assess the robustness of the disposal system in light of issues such as potential exposures and associated uncertainties.

(58) Potential exposures may occur as a result of an accident at the facility or natural disruptive event. The risk associated with such events is a function of the probability of the event causing a dose, the magnitude of the exposure and the probability of detriment due to that dose. For the detriment component of this function, the nominal probability coefficients for workers and the general population for stochastic effects from low-LET radiation (Table 1 in *Publication 103* (ICRP, 2007) can serve as a reference, adjusted as necessary to suit specific protection purposes. Risk constraints are applied to potential exposures when reasonable estimates of probabilities of occurrence of the event or combined events can be made or when the probability or likelihood of occurrence can be bounded. In such a case, an aggregated approach combining the probability of a dose occurring multiplied by the probability of the resulting health effect can be applied. The risk constraint, just as a dose constraint, serves as a point of departure for efforts to optimise protection by addressing both probability of an event and the resulting health effect.

(59) For potential exposures of workers, the Commission continues to recommend a generic risk constraint for fatalities (mainly cancer later in life) of 2×10^{-4} $year^{-1}$. For potential exposures of the public, the Commission continues to recommend a risk constraint of 10^{-5} $year^{-1}$ (ICRP, 2007). If a probabilistic approach is not adopted in the assessment of accidents, use can be made of the bounding reference levels for the appropriate exposure situation. Whilst the numerical values of risk provide a point of reference, when considering the safety of a near-surface disposal system, they should be used primarily to gain an understanding of its performance and robustness, rather than as an absolute measure of its safety. It should be noted that an optimised system may result in a distribution of doses where some could be predicted to be above the applicable dose constraint. Any assessed scenario indicating exceedance of the values should be investigated in more depth to

determine the appropriateness of assumptions, levels of uncertainties, validity of applied computational codes, and other features of the assessment. An evaluation of potential exposures and the suite of scenarios (including waste characteristics, possible external degrading mechanisms, etc.) can be used to support and explore design criteria of the protective actions considered.

(60) The actual design basis for a near-surface disposal system should be substantiated and optimised in accordance with the exposure situations for workers, the public, and the environment and the related criteria as summarised in Table 1 below. The facility must be designed to protect workers and the public from expected operating conditions and accidents or disturbing events during the development and operation of the facility and after its closure. The effective dose limit for workers of 20 mSv year^{-1} averaged over five consecutive years is applied with the requirement of optimising protection below dose constraints and in the case of the environment Derived Consideration Reference Levels (DCRLs) are used. For the exposure of the public the effective dose limit is 1 mSv year^{-1} from all sources with a dose constraint of not more than 0.3 mSv year^{-1} for each source. For potential exposures of the public in the case of an aggregated approach, a risk constraint of 1×10^{-5} year^{-1} is recommended. Beyond design basis events that are extremely unlikely to occur are considered outside the scope of the assessment and not considered in optimisation. If such scenario were to occur in the future, the competent authorities of the time would assess whether reference levels for emergency and/or existing situation currently used would be applied as appropriate.

Table 1. Recommended Radiological Protection Criteria and Objectives for Near-Surface Disposal

Phase	**Activity/Scenario**	**Protective approach**	**Criteria**	**Planning framework**
Pre-operational & Operational	Site preparation; Design; Construction; Waste emplacement; Closure	Planned exposure situation, implementing: • Dose limits • Constraints (dose and risk) • Derived Consideration Reference Levels (DCRL)	Optimisation as for the design and operation of any facility	Design basis
Post-closure	Expected evolution of facility and environment including foreseeable disruptive events		Optimisation guided by constraints of 0.3 mSv year^{-1} (dose); 10^{-5} year^{-1} (risk); and lower end of relevant DCRL	
	Natural disruptive events or Inadvertent human intrusion	Existing (and/or Emergency) Exposure Situation, implementing: • Reference levels • DCRL	Optimisation guided by reference levels ≤ 20 mSv and DCRLs	
	Extreme events; Accidents	Evaluation against possible consequences; BAT	Not considered in optimisation	Beyond design basis

(61) The results of estimating risk over long periods of time should be interpreted cautiously, because of the additional inherent uncertainties in and the challenges of

estimating probabilities of events in the distant future. A bounding approach to estimating probabilities making use of cautious, but realistic parameter values, may be used in addressing these challenges. It should be noted that the use of compounding of overly cautious assumptions may lead to overly conservative bounding estimations of little practical relevance, and this should be avoided.

(62) The comparison of calculated dose and risk with constraints or reference values is a way to check if the system as designed and developed through a process of optimisation of protection can reasonably meet the protection targets and criteria. For example, if the exposures from long-lived radionuclides could exceed the recommended reference levels e.g., in the event of inadvertent human intrusion, the waste should be disposed with greater emphasis on isolation. In such an approach, the emphasis is primarily on the design of the facility and on the quality of the construction and operation of the facility and conformance with safety standards and requirements that apply. Radiological assessments of the facility design and operation are only one specific way to check this quality. It is also a way to assess if the residual hazard posed by the projected disposed source term after an assumed period of institutional control is acceptable from a radiological protection point of view due to both radionuclide migration and inadvertent human intrusion.

3.4. The representative person

(63) The Commission considers that its recommendations on the estimation of exposures in *Publication 101* (ICRP, 2006) apply as general guidance. The Commission recommends that for planned exposure situations, exposures of members of the public should, in general, be assessed on the basis of the annual effective dose to the representative person.

(64) During the post-closure phase of a near-surface disposal facility, due to the time scales under consideration, the habits and characteristics of the representative person, as well as the characteristics of the host environment, are subject to uncertainties. Since there is limited scientific basis for predicting the nature or probability of future human actions, any such representative person has to be hypothetical and stylised. The habits and characteristics assumed for the individual in the future should be chosen on the basis of reasonably conservative and plausible assumptions, considering site- or region-specific information as well as biological and physiological determinants of human life. Moreover, in many cases, different scenarios, each associated with its own representative persons, may be considered for the distant future and each scenario has a different likelihood. Thus, the scenario leading to the highest calculated dose may not be linked to the highest risk. It is therefore important for decision makers to have a clear presentation of the different scenarios, including the associated doses and likelihoods, and the basis for their choice.

(65) As stated in *Publication 101* (ICRP, 2006), for the purpose of protection of the public, the representative person corresponds to an individual receiving a dose that is representative of the more highly exposed individuals in the population. Therefore, it should be assumed that the representative person has a reasonable upper bound of the potential doses from the various exposure pathways, with due regard to the assumed climatic conditions for that evolution scenario (e.g. considerations of ice coverage, desertification, etc.). This is an assumption as humans may no longer inhabit areas in the distant future.

(66) A representative person cannot be defined independently of the assumed biosphere. Major changes may occur in the biosphere in the long-term and consideration needs to be given to potential changes. A representative person and biosphere should be defined using either a site-specific approach based on site- or region-specific information, or a stylised

approach based on more general habits and conditions; the use of stylised approaches will become more important for longer time scales.

(67) The Commission recommends (ICRP, 2006) the use of three age categories for the prospective estimation of annual dose to the representative person for comparison with annual dose or risk criteria. The annual dose from the intake of a radionuclide already includes a component relating to the fact that the radionuclide will deliver a dose in successive years, the length of time being determined by the biological half-life of the radionuclide in the body. *Publication 101* (ICRP, 2006) concludes that consideration of three age groups, 1-year and 10-year-old children and adults, is sufficient for most dose assessments, especially for long-term exposures when individual cohort members will naturally proceed through age groups. In general, uncertainties in estimating exposures are large in comparison with differences in dose coefficients for different age-groups. It is recognized that stakeholders may make requests for calculation of additional age groups, and such calculations may be appropriate to facilitate dialogue. In the case of near-surface disposal, any exposures are expected to occur in the future, and to be associated with levels of radionuclides in the environment that change slowly over the time scale of a human lifetime. Given the inherent uncertainties in calculations extending to the distant future, the dose or risk to an adult representative person will adequately represent the exposure of a person representative of the more highly exposed individuals in the population.

3.5. Optimisation of protection

(68) The principle of optimisation is defined by the Commission (ICRP, 2006, 2007) as the source-related process to keep the likelihood of incurring exposures (where these are not certain to be received), the number of people exposed, and the magnitude of individual doses as low as reasonably achievable, taking economic and societal factors into account. Guidance for the optimisation process is described in *Publication 101* (ICRP, 2006). In addition, *Publication 103* (ICRP, 2007) provides the following advice that is very relevant to the issue of near-surface disposal:

> *(214) Optimisation is always aimed at achieving the best level of protection under the prevailing circumstances through an ongoing, iterative process that involves:*
>
> - *evaluation of the exposure situation, including any potential exposures (the framing of the process);*
> - *selection of an appropriate value for the constraint or reference level;*
> - *identification of the possible protection options;*
> - *selection of the best option under the prevailing circumstances; and*
> - *implementation of the selected option.*

(69) The ICRP principle of optimisation of radiological protection when applied to the development and implementation of a near-surface disposal system has to be understood in the broadest sense as an iterative, systematic, and transparent evaluation of options for enhancing its protective capabilities and for reducing its radiological impacts. Optimisation also should be considered holistically within the context of the broader national waste management policy and strategy when deciding the type and location of disposal facilities considering both radiological impact and non-radiological aspects such as chemical hazards and transport safety. Optimising protection requires value judgements and stakeholder

involvement in this process is important. The ethical values in the system of radiological protection provide a framework for engaging in these discussions.

(70) Optimisation of protection has to deal with the main aim of disposal systems, i.e. to protect humans and the environment, now and in the future, by containing the radioactive substances in the waste and by isolating them from people and the environment and by protecting the facility from external degrading mechanisms. That goal must be met during the operational period and protection of future generations and the environment beyond closure of the facility including a time when it is assumed that there is no oversight over the facility. In the long term and particularly when no active oversight is in place, protection of people and the environment has to be maintained with a reasonable level of assurance by a passively functioning disposal system. Optimisation of protection has to consider the balance between passive and active measures of safety, for example, when deciding on the duration and nature of institutional control measures.

(71) An iterative decision-making process for near-surface disposal system development and implementation provides a framework for the optimisation process. The optimisation process should be focused on a realistic number of design options relevant to the site and inventory and making use of clear targets and end points. Optimisation has to cover all elements of the disposal system in an integrative approach (i.e. site characteristics, facility design, waste package design, waste characteristics, supervision and control measures), as well as all relevant time periods.

(72) Optimisation of protection is the responsibility of the facility operator and involves liaison with regulatory authorities and stakeholders. Agreement should be reached on what constitutes a clear and reasonable range of relevant options to be implemented.

(73) The focus of the optimisation process differs for the design, operational, and post closure phases. The greatest opportunity to optimise protection is in the design phase and as such should be given a high focus. The opportunity for optimisation during operation will be less. Optimisation of operational safety will be undertaken in a similar manner as other operational nuclear facilities, but also can influence post closure safety.

(74) Judgement of the quality of the near-surface disposal system has to be made, and reviewed critically when needed, in a well-structured and transparent process, with the involvement of all relevant stakeholders. At the heart of this process is the interaction, transparent for all other stakeholders, between the developer and the safety authorities.

(75) The Commission recognizes that societal factors (including policy decisions and risk acceptance issues) can bound the optimisation process to various extents, such as by defining certain conditions (e.g. site location, retrievability). It is important that these considerations are identified in a manner transparent to all involved stakeholders, and that their protection implications are understood (OECD/NEA, 2011).

(76) Although optimisation is a continuous process, all stakeholders should be afforded the opportunity to judge the result of the process and provide feedback. The Commission recognizes that not all stakeholders will agree with all aspects of a complex decision-making process, but urges that the process and approach used in the optimisation and stakeholder involvement provide an adequate basis for all concerns and issues to be openly and constructively identified and addressed.

(77) Nearly all aspects of optimisation of protection for the post-closure phase will happen prior to waste emplacement, largely in the design phase, with the plans to close the facility being part of the design phase. Some further optimisation of protection could be provided during the operational phase; for example, new materials or techniques may become available. Experience gained during the closure of parts of the facility (e.g. individual disposal cells) can lead to improvements in planning for the closure of the overall facility,

however, any such improvements should not be seen as requiring modification of waste already disposed unless it is found that adequate protection is no longer being afforded.

(78) Near-surface disposal facilities are sited, designed, constructed and operated to provide for robust long-term containment and isolation, in order to avoid any significant impact on humans and the environment. The assessment of post-closure radiological impacts through the estimation of effective dose or risk to a representative person and doses to biota presents challenges. This is due to the various categories of uncertainties related to radiological dose and risk calculations. It provides an illustration of the robustness of the system, rather than precise predictions of future radiological consequences. Thus, when considering the distant future, dose and risk values lose their intrinsic meaning and only retain value as providing an enveloping estimate of potential radiological impact. With such an approach, calculated dose and risk in the future might not be discriminating factors between design options. In fact, when radiological assessments systematically show that for all selected scenarios the dose criteria are met with reasonable margins and only very unlikely scenarios indicating exceedance and when no obviously better design options are available, the radiological optimisation process can be considered successful.

(79) The elements guiding or directing the optimisation process should be those that directly or indirectly determine the quality of the components of the facility as built, operated, and closed, where quality refers to the capacity of the components to fulfil the functions of containment and isolation in a robust manner. The assessment and judgement of the quality of system design and system components essentially includes the site characteristics, as well as the concepts of good practice, sound engineering, and managerial principles. The optimisation of radiological protection supports the design process but provides less information on protective capability in the distant future, whereas sound design and system performance should dominate decisions for the best outcome of the optimisation process in the long term. In addition, when dealing with safety in the distant future optimization can be complemented and supported by applying the concept of BAT to the various phases of the disposal system. The use of BAT should consider should consider their efficacy, economics and applicability to particular situation.

(80) The way in which the various elements of a disposal system can be optimised in an integrative manner during its development varies widely. First, step-by-step optimisation decisions mainly have to be taken in chronological order (e.g. the decisions on the choice of one or a limited number of sites are often prior to decisions on a detailed design). For the selection of a site, a balance has to be made between technical criteria related to the safety of a disposal system (long-term stability, barriers for radionuclide migration, absence or presence of natural resources in the vicinity), and local economic and societal factors. With regard to societal factors, the acceptance of a facility from the local community is a key issue and requires effective stakeholder engagement. Favourable sites can, in a first step, be identified on the basis of broadly defined ‘required qualities’, taking due account of the containment and isolation functions that can be provided by the disposal system.

(81) If several suitable sites can be identified and evaluated, the decision in favour of one specific site will always be a multifactorial decision, based on both quantitative and qualitative judgements. Radiological assessment will be one of the factors, but will be unlikely to dominate the decision due to its preliminary nature and all the associated uncertainties at this stage.

(82) Assessment of the robustness of the disposal system is a major contribution to system optimisation and should be presented in the safety demonstration. It provides both quantitative and qualitative insights into the performance of the disposal system and its components, and into their relative contributions to the overall system safety and how this

can be affected by disturbing events and processes. The assessment also identifies areas for design enhancement and the need for high levels of quality assurance so that optimisation can be achieved by both improving the design and highlighting areas where it is important to focus resources and effort.

3.6. Protection of the environment

(83) Demonstrating that the environment is, or will be, protected against the harmful effects of releases from facilities is often a requirement in national legislation, and in relation to many human activities, including the management of radioactive waste. ICRP has responded to this need, as well as to a number of other requirements of an ethical nature (ICRP, 2003), by addressing environmental protection directly and specifically in *Publication 103* (ICRP, 2007), and by offering a methodology to address this issue, as outlined in *Publication 108* (ICRP, 2008) and further elucidated in *Publication 114*, *124*, and *136* (ICRP, 2009c, 2014a, 2017a).

(84) The ICRP approach considers the protection of the environment by virtue of the aim of 'preventing or reducing the frequency of deleterious effects on fauna and flora to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health status of natural habitats, communities and ecosystems (ICRP, 2007, Para. 30). In addition to natural ecosystems, consideration should be given to ones that are heavily influenced by humankind and provide various essential services to people. For added clarity, the ICRP approach considers the effects of radioactivity in the environment and not just the mere presence of a radioactive substance in the environment as part of the protection aim. The environmental impact would normally be assessed through an environmental impact assessment process that will consider radiological impacts and also a broader range of factors such as visual impact, chemical toxicity impact, noise, land use, and impact on amenities. It is expected that this process would solicit input from stakeholders on the various aspects of a project involving a waste disposal facility.

(85) The default tool for demonstrating protection and determining whether any protective actions are needed for radioactive waste facilities over the long-term should be the set of Reference Animals and Plants (RAPs) DCRLs that has been described by ICRP and for which the relevant data sets and dose criteria have been derived (ICRP, 2008, 2009c). This set was deliberately chosen because its components are considered to be typical biotic types of the major environmental domains of land, sea, and fresh water. A set of representative organisms appropriate to the specific facility will need to be chosen and these may need to vary from the default RAPs. Stakeholder involvement is important to help guide the choice of RAPs.

(86) Over the long-time frames that are considered for near-surface disposal facilities, the biosphere is likely to change and may even change substantially. Such changes may entail biosphere evolution with time, that is either natural or is enhanced or perturbed through human action, for example, climate change. Thus, use of the RAPs should provide at least one point of reference for considering, if necessary, the likely dose and effect in any existing or altered species in the future. In some cases, the choice of the representative organisms for a particular situation may not be well represented by the default RAPs and the differences will need to be assessed (ICRP, 2014a).

(87) The assessment of doses to relevant representative organisms, as represented by the appropriate RAPs, involves an environmental pathways analysis that consider both internal and external sources of radiation. The calculated absorbed dose rates are compared with the

appropriate DCRLs that are specific to each type of RAP (ICRP, 2008). A DCRL is as a band of dose rate, spanning one order of magnitude, within which there is some chance of deleterious effects from ionising radiation occurring to individuals of that type of RAP that may lead to consequences at the population level. Thus, when considered together with other relevant information, DCRLs can be used as points of reference to inform on the appropriate level of effort that should be expended on environmental protection, dependent on the overall management objectives, the exposure situation, the actual fauna and flora present, and the numbers of individuals thus exposed.

(88) In the context of a near-surface disposal facility as a planned exposure situation the lower boundary of the relevant DCRL band should be used as the appropriate reference point for the protection of the relevant RAPs. If dose rates are within the bands, the Commission believes that consideration should be given to reduce exposures, assuming that the costs and benefits are such that further efforts are warranted (ICRP 2014a). In the unlikely event of an emergency exposure situation or an existing exposure situation developing after a breakdown of controls, if the dose rates are above the relevant DCRL band, the Commission recommends that the aim should be to reduce exposures to levels that are within the DCRL bands for the relevant populations, with full consideration of the radiological and non-radiological consequences of so doing.

(89) The use of RAPs and DCRLs offers an additional line of argument and reasoning in building a safety case using endpoints that are different from, but complementary to, protection of human health. Nevertheless, both human and environmental factors contribute to the most appropriate selection of the disposal alternative and optimisation. This includes incorporating radiological environmental protection considerations into the overall radiological optimisation process. Consideration of environmental protection will broaden the basis for risk-informed decision making and stakeholder involvement is critical for understanding the potential wide range of environmental issues.

4. IMPLEMENTATION OF THE SYSTEM OF RADIOLOGICAL PROTECTION TO THE PHASES OF A NEAR-SURFACE DISPOSAL FACILITY FOR RADIOACTIVE WASTE

(90) The lifetime of a near-surface disposal facility involves three main phases; pre-operational, operational and post-closure, the durations of which vary between national programmes and the needs of individual facilities. The Commission recommends that the process for engaging members of the public and all relevant stakeholders should be defined from the beginning reflecting the ethical and procedural values noted earlier.

(91) By disposing radioactive waste, the management option is deliberate and clearly planned. There is an obligation to provide controls to ensure that during the operational and post-closure phases of a near-surface disposal facility an optimised level of protection is ensured. These controls are in the first instance in the siting and design step, when decisions on design concepts are taken, and in the second instance in the operational step when system implementation has to be in conformity with design requirements. In some situations, design modifications may be introduced to deal with changing circumstances. However, circumstances, which may not be part of the expected evolution of the facility, may arise and they may lead to deviations from the expected evolution; they are discussed below.

(92) Oversight is important to help ensure the controls are appropriate and continue to function properly. Various types of oversight are associated with these phases and may vary in type and extent and may be direct or indirect.

(93) Direct oversight refers to active measures before operation (siting, design, and construction), during operation (waste receipt and emplacement, facility development and facility closure) and in the immediate post closure phase (maintenance and monitoring), carried out by the operating organisation and relevant authorities. Direct oversight includes such activities as review and assessment, authorisation, inspections and monitoring. It includes regulatory supervision and inspection, preservation and establishment of societal records, and societal memory of the presence of the facility.

(94) Part of the oversight of the facility should involve a regulatory review and assessment of the safety case developed by the operating organisation that presents all the evidence and assessment, supporting the safety of the facility, both during operation and post-closure. The safety case should be updated periodically as experience and new information is gained and specifically for major steps in the facility development, operation and closure. The safety case should be agreed to by the regulatory authority prior to all the major development steps and can include acceptance of the site, development of the design, construction of the facility, modifications of design and construction as informed by new information and experience, operation of the facility, closure of the facility and the end of the period of direct oversight. Post-closure arrangements will be addressed by the safety case, as well as any significant modification to the design, facility operation or waste type or form accepted for disposal at the facility.

(95) The regulatory authority should set conditions of authorisation for each step in the development, operation and closure of the facility and for a period of time after closure until termination of the disposal facility authorisation. An important condition will be the waste acceptance criteria for waste to be disposed in the facility. Another important condition will be the management system established and implemented by the operator that will provide assurance of the quality of all safety-related work throughout the lifecycle of the disposal facility. The regulatory authority should also put in place a programme of compliance

assurance to ensure the operator complies with all the conditions of authorisation and any other legal obligations.

(96) During the siting, design, construction, operation, closure and into post-closure, direct oversight of the near-surface facility should be performed consistent with the regulatory framework. Following closure of the facility, direct oversight may continue for a period of time and include monitoring of the performances of the near-surface disposal facility and potential exposure pathways, periodic updates of the safety case, the preservation of records of the facility and verification of access control and land-use restrictions.

(97) During the period after closure, access to the site should, if required, be actively controlled and monitoring arrangements put in place to confirm the adequacy and effectiveness of the safety functions providing containment and isolation. The regulator will need to assess when it has sufficient confidence in the long-term performance of the facility to release the operator from its obligation of the management of the site. This will include factors such as the levels of controls needed to prevent unacceptable impact from inadvertent human intrusion and the establishment of an adequate form of any necessary indirect oversight. In addition to these factors, the Commission recommends that the decision to withdraw direct regulatory oversight should be taken with the participation of all relevant stakeholders.

(98) Indirect oversight refers to the period after closure when the authorisation from the regulatory authority has been terminated, the authorised disposal facility operator will no longer be present at the site, and oversight is exercised by a designated governmental authority. The authority will take care of land-use control, preservation of records, and continued monitoring might be undertaken to check that the environmental conditions are not degrading. Eventually, there may be a time when the memory of the presence of the near-surface disposal facility is lost, and society no longer exercises any oversight over the site.

(99) The continuation of oversight during the long-term becomes more uncertain at later times (e.g. hundreds of years). From a prudent approach to safety, especially in the design stage, it must be assumed that at some point in time, memory of the facility will be lost and there is no further oversight, although the aim is not to lose the memory of the site. This is one reason for careful site selection and why strict control should be exercised over the longer-lived radionuclide content in the waste disposed, and that facilities are developed and designed not to rely on oversight in the distant future (i.e. providing passive safety features). The safety case would exam these issues and potential releases to the environment.

4.1. The pre-operational phase

(100) The pre-operational phase is of high importance for the safety of the near-surface disposal facility in the long term, and decisions made at this stage have to take into consideration all the required safety principles and requirements, applicable radiological criteria, and recommendations adopted from stakeholder feedback. During this phase, a suitable site is selected and characterised, the disposal facility is designed for an assumed inventory and against defined regulatory criteria, and the engineering feasibility and adequacy is demonstrated. Supporting research and development work is undertaken, including environmental monitoring around the intended facility.

(101) A safety case including safety assessment for the operational and post-closure phases is developed by the operator that must address the operational and the post-closure phases and, specifically, the longer-term future when controls and interventions cannot be relied upon. The aim of the developed safety case is to provide confidence that disposal

system as designed and operated will protect workers, the public, and the environment. The safety case is an essential input to all important decisions concerning the disposal system. It has to provide the basis for understanding the disposal system and estimating how it will behave over time. It has to address site aspects and engineering aspects, providing the logic and rationale for the design, and has to be supported by safety assessment. It also has to address the management system put in place to ensure quality for all aspects important to safety. At any step in the development of a disposal facility, the safety case also has to identify and acknowledge the unresolved uncertainties that exist at that stage and their significance, and the approaches for their management. It has to include the output of the safety assessment together with additional information, including supporting evidence and reasoning on the robustness and reliability of the facility, its design, the logic of the design, and the quality of safety assessment and underlying assumptions.

(102) The facility design will largely be determined on the basis of sound and proven engineering practice complemented by optimisation studies, assessment of robustness and consideration on the defence-in-depth concept (see Section 3.5 Optimisation of Protection). Nevertheless, and despite the uncertainties mentioned above, calculation of doses is undertaken at the design stage of a disposal facility in order to assess the adequacy of the facility design in respect of its containment and isolation functions under the range of evolution scenarios agreed for assessment and also for the consequence of inadvertent human intrusion. Cautious, but realistic assumptions should be made for the various categories of uncertainties in order to avoid underestimation of potential future radiological consequences of a near-surface disposal facility.

(103) The accumulation of cautious assumptions, as part of an approach to bound potential future impacts (rather than trying to predict actual doses), leads to important consideration having to be given to the margins of bounding. However, it is important to avoid compounding unduly conservative assumptions that can result in completely unrealistic outcomes. The application of the ethical values of prudence and transparency are important ensuring confidence in the calculated outcomes. Numerical compliance with dose criteria alone should not compel acceptance or rejection of a near-surface disposal facility, further consideration should be given to the levels of conservatism and the outcome of sensitivity and uncertainty assessments.

(104) Participation of the various stakeholders should be undertaken to enhance the quality of the decision-making process for the pre-operational siting, design and authorization activities. For example, stakeholder participation will bring local knowledge to the project, the input of local values will help the optimisation process, and this engagement will help keep the societal memory of the project alive. Stakeholder participation is not just another step in the process, regardless of the associated practical benefits, but is one of the three procedural ethical values in the system of radiological protection and requires the other two, i.e. accountability and transparency, to be truly effective. As noted previously, accountability has both the aspects of emphasizing that those in charge are answerable for their actions and intergenerational justice, which is an important issue for waste disposal. Transparency enables social oversight and vigilance of the public by ensuring fairness of the process through which information is intentionally shared. These three procedural values are mutually reinforcing and are an important element of good governance principles, aided by an effective regulatory process to help ensure the successful integration of the technical and social aspects of any project.

(105) Within the broad level of effort required to meet the appropriate dose constraints, decisions will be required as to where to focus limited resources to achieve the desired results and this requires a broad engagement with all stakeholders to be successful. For example,

this dialogue can help stakeholders contribute to the decision-making process and come to a mutual understanding on the balance between efforts to reduce expected dose (i.e. the mode of distribution of predicted doses) versus the width of the distribution of doses (Ogino et al, 2019). It maybe decided that once predicted doses achieve a particular level, further efforts are better directed at better quality control to reduce the uncertainties in parameters and achieve a narrower or more equitable range of predicted doses. By engaging the stakeholders in this discussion, stakeholders can make an informed decision in a transparent manner.

(106) A baseline monitoring programme of the extant environmental conditions should also be established prior to development of the disposal facility. The programme should include both radiological and non-radiological parameters such as climate and hydrology, for use in future confirmation of the performance of the functions of the facility.

(107) The development of an adequate legal and regulatory framework for this phase should be assured, setting down safety principles, regulatory process, radiological protection and radioactive waste classification criteria and providing regulatory guidance. Appropriate mechanisms for formal and structured dialogue between the regulator and operator and with stakeholders should also be established and the due regulatory process followed involving application, review and granting of authorisation. This point touches again upon the importance of the ethical procedural values of stakeholder involvement, accountability, and transparency.

4.2. The operational phase

(108) During the operational phase several distinct kinds of activity may take place; construction of the disposal infrastructure, waste emplacement, and capping/sealing and these activities may occur simultaneously.

(109) The disposal facility is constructed, the waste is emplaced, and the facility units are closed according to the site-specific design and some site landscaping work may be carried out. The end of the period of active site disposal occurs when emplacement activities are complete, including any waste from decommissioning activities at the site. There may then be a period of observation prior to the final closure of the facility. The effective application of the management system is to provide: 1) a high level of assurance of the quality of all construction and closure related work, 2) a high level of assurance of compliance with the waste acceptance criteria and design prescription, is critical, as limited opportunity will be available for corrective actions. Having this high-level of assurance of the proper execution of the project is key to ensure the radiological criteria incorporated into the design of the project are met both in the operational phase and post closure. During the operational phase, it will be possible to continue to evaluate the protective capability of the disposal facility based on regular updates of the safety case, with a view to developing a high level of assurance of its future safety. This phase is under direct oversight of the regulatory authority, and should include exchanges with other relevant stakeholders.

(110) As the facility starts to handle radioactive waste, occupational radiation protection must be addressed within the context of the applicable regulatory regime. As waste disposal is nominally a planned exposure situation, the occupational exposures would be expected to be managed within the applicable dose constraints and limits. The environmental conditions are monitored continuously and compared with the baseline data. Research and development may continue to confirm site characteristics and behaviour of the engineered components and the overall design. The regulator should perform regular compliance assurance activities including inspections of the disposal operations. The safety case should be updated

periodically by the operator and for any major modification and reviewed by the regulator. In this phase, new disposal capacity may be constructed and covered. This period may cover several decades and changes may take place during this period arising from operational experience feedback and the ongoing optimisation process and improvements in knowledge, safety issues etc. Any such changes must be carefully considered in terms of the safety case and any implication for operational and post-closure safety carefully evaluated. Changes could also take place that are outside of the control of the operating organisation. These could include changes in land use in the local site environment or could include changes in population distribution and industrial and societal activities in the site environs. Changes in local climate may also occur. The implications of such changes or relevant new information should be considered during periodic reviews of the safety case. All changes and their safety implications should be subject to regulatory process and associated stakeholder involvement.

(111) The final closure activities (e.g. backfilling, grouting, sealing and covering) are performed according to the approved design for its final state. Access to the disposal areas will be terminated. Monitoring and access control provisions are put in place. Surface facilities may be dismantled and all final surface contouring, vegetation and drainage provisions are put in place. All relevant information is preserved in a purpose developed archive system, and any site markers for future generations are emplaced. All these closure activities should be subjected to the regulatory process and stakeholders should be involved in the disposal facility closure process.

4.3. The post-closure phase

(112) During the post-closure phase oversight over access controls to the site should be maintained to reduce to the extent practicable the likelihood of inadvertent human intrusion. Monitoring should be continued to confirm the ongoing performance of containment and isolation features and any maintenance or repair considered necessary should be carried out. These activities should be carried out within the prescribed regulatory framework with the authorized organization undertaking the work having all the necessary technical and scientific skills. The period of time over which these activities continue will depend on the inventory disposed in the facility and how long it takes to establish confidence in the long-term performance of the facility. This includes meeting the reference level for the scenario of inadvertent human intrusion. In this regard, *Publication 103* (ICRP, 2007, para 287) recommends a reference level from 1 to 20 mSv. For dealing with a situation with off-site impacts that is being addressed as an existing exposure the Commission recommends the lower end of the range of 1 to 20 mSv. This sets the stage for the release of the direct responsibility and management of the facility from the operator to next phase for the facility.

(113) Once a decision has been made to release the operating organisation from its regulatory obligations, the level of oversight in the next phase should be consistent with the needs articulated in the safety case. For example, this could involve the transfer of obligations from the operator to an appropriate government authority. Such a decision would be taken in the context of the existing regulatory framework and would need to consider technical factors and the views of stakeholders. Key to this process will be the confidence that the regulatory authority and the stakeholders have in the long-term performance of the containment and isolation features controlling release and migration of radionuclides from the facility, as articulated in the safety case. In this regard, the successful implementation and integration of the procedural ethical values of accountability, transparency, and stakeholder participation throughout the project should help with building this confidence, assuming the

facility has performed according to the safety case. Assuming there would be a period of some form of institutional control to ensure conditions assumed in the post-closure safety case remain valid to help ensure the long-term radiological criteria continue to be met, the regulatory authority would need to make decisions on issues such as controlling land use and the need for periodic inspections of the site. It must also be assumed that at some time in the future control could cease by a deliberate decision or the loss of memory of the site. This is the reason to maintain oversight until confidence that the regulatory criteria for the long-term performance, including those for inadvertent human intrusion, are satisfied.

4.4. Protection in particular circumstances

(114) There may be situations that develop during the life of a facility that require the re-evaluation of safety beyond the periodic reviews of performance against the safety case. Examples could include the introduction of new waste types to an operating facility; new scientific information, e.g. from material testing or environmental monitoring; changes in the performance in a closed facility; or "re-discovery" of a previous disposal facility.

(115) If the re-evaluation of safety occurs prior to closure, the facility continues to be considered as a planned exposure situation as operations are ongoing, and design and inventory modifications may be possible, subject to regulatory approval, before transition to indirect control. For unanticipated situations after closure of a site, the ability to modify the barriers and control of the source term is usually more limited. In circumstances with serious degradation or failures of the barriers it may be decided to consider the facility as an existing exposure situation, using the principles of optimisation and reference levels to determine the appropriate protective actions in consultation with the stakeholders. The decision to treat the situation as an existing exposure situation would depend upon a variety of factors and an important one would be the extent of any offsite contamination. The ICRP recommends a reference level within the lower half of the 1 to 20 mSv/year band with the objective to progressively reduce exposures to levels towards the lower end of the band or below if possible. While protective actions below 1 mSv/year may not be justified, this would be determined by the consultation process with national authorities, regulators and stakeholders.

(116) When developing a disposal facility decisions have to be taken as to what conditions, events and processes are considered in the design basis and what events can be excluded. These considerations should involve dialogue between the operator, the regulator and other stakeholders, and should make use of the broad international experience developed to date in the design and assessment of near-surface disposal facilities. Independent peer review of the design basis is also considered a valuable and necessary process. It is expected that a similar process would be used in making decisions in dealing with unanticipated situations in the post-closure phase that have significantly compromised the design basis of facility.

(117) When considering extremely rare events that are excluded from the design basis, it may be appropriate to estimate the potential radiological impact by use of stylised scenarios. The results of those analyses can be expressed as dose or risk and used as indicators of system robustness, and provide insight to the design process. The treatment of extremely rare events could vary between sites, depending on the characteristics of a site that make it more or less vulnerable to disturbing events, and between different national approaches, depending on what events are, or have to be (perhaps for culturally sensitive reasons), included in the design basis. Because inadvertent human intrusion could occur after the institutional control period due to the location of a near-surface disposal facility in the biosphere, this scenario should be included in the design basis. For this situation or other disruptive events, risk

constraints may be applied to the resulting potential exposures when reasonable estimates of probabilities of occurrence of the event or combined events can be made or when the probability or likelihood of occurrence can be bounded.

4.4.1. Natural disruptive events

(118) The disposal facility and its surrounding environment could be impacted or altered by natural disruptive events (e.g. earthquake, severe flood) and their impact should be taken into account in the design of the facility. Regarding the potential events that may occur long after closure, different scenarios can be envisaged according to current knowledge. Events for which it is possible to estimate or bound the probability and time frames of occurrence are normally included in the design-basis scenarios.

(119) Natural disruptive events with very low probability, i.e. $\lesssim 10^{-6}$ year^{-1}, compared with the design basis may occur, and some of these could induce significant disturbances to the disposal facility or change radionuclide migration rates. Examples of these types of events would be largely site dependent (e.g. major landform change due to landslide). The Commission recommends the establishment of a methodology addressing these events which could include a process for excluding very low-probability events from consideration in the risk-assessment process, selecting a site with characteristics that minimise the probability of such events, and/or assessing specific events through stylised assessments (ICRP, 2013).

(120) The Commission recommends that the two different groups of natural disruptive events should be considered separately. For events that are included in the design-basis, the Commission recommends application of the risk constraint or the dose constraint for planned exposure situations. For very-low probability events not taken into account in the design-basis, application of the risk constraint or the dose constraint for planned exposure situations does not apply. Nevertheless, the results of assessing very-low probability events may provide insights into potential design improvements. Decisions on which events have to be included in or excluded from the design basis should be made prudently and in a transparent manner.

(121) Should a disturbing event occur and cause degradation of a disposal facility such that dose constraints (or the environmental DCRLs) are exceeded long-lasting exposure resulting from such natural disruptive events (with or without an emergency phase) should be referred to as 'existing exposure situation' and the recommended reference level for optimising protection strategies should be in the lower range of the band of 1 to 20 mSv year^{-1}. Notwithstanding that past decisions may have been made about the reference level, it should be re-examined and established in agreement with the regulatory authorities and relevant stakeholders at the time of the event taking into account the prevailing circumstances. In addition, other activities associated with the facility may need to be re-examined in consultation with the stakeholders, such as environmental and health surveillance monitoring.

4.4.2. Inadvertent human intrusion

(122) Waste is disposed of in a near-surface disposal facility for the purposes of containment and isolation, one aspect of which is avoidance of inadvertent human intrusion. When deciding in favour of near-surface disposal of low- and very-low-level waste, as compared to other possible disposal options (geological disposal), account has to be taken of the potentially higher possibility of inadvertent human intrusion, because of the location of the facility on or near the surface (i.e. in the accessible biosphere), requiring specific

protection measures to be taken such as activity limitation and control measures for the time period of a few hundred years when significant doses (i.e. in excess of the adopted reference level) are possible.

(123) In the case where oversight provisions are no longer in place and the memory of the presence of the near-surface disposal facility is assumed to be lost, it is possible that people will ‘rediscover’ the facility. This may be without compromising its integrity (e.g. remote sensing), by detecting radionuclides in the biosphere, or it may be by directly breaching the containment, albeit inadvertently, and causing exposure to people and contamination of the environment. When assessing such situations, they should be treated as existing exposure situations and justified protective actions taken as necessary.

(124) It is necessary to distinguish between deliberate and inadvertent human intrusion into the facility. The former is not discussed further in this report as it is considered to be out of the scope of the responsibility of the current generation to protect a deliberate intruder (i.e. a person who is aware of the nature of the facility) because by its nature a deliberate intruder has bypassed any relevant controls that are in place. In addition, human actions resulting in disturbance beyond the disposal facility in the surrounding environment (e.g. road construction, change of land use to agriculture) are not categorised as human intrusion. It is assumed that the siting and design of the facility have included features to reduce the possibility of inadvertent human intrusion.

(125) An intrusion event will compromise the barriers that have been designed into the disposal facility. As a future society may be unaware of exposures resulting from inadvertent human intrusion, protection features to reduce such exposures, or their likelihood should be considered and implemented as appropriate during the development of the disposal facility through siting and design.

(126) Protection from exposures associated with inadvertent human intrusion is in the first instance accomplished by imposing limits on the radionuclide content and distribution in the disposal facility, and secondly by efforts to reduce the possibility of such events. These may include selecting sites with little assumed valuable resources (mineral and other deposits, water resources, agricultural/industrial/residential land) based on current societal values to reduce the potential for inadvertent human intrusion, incorporating robust design features that make intrusion more difficult, or from provisions for direct oversight (e.g. surveillance of the site by operator under regulatory control) and indirect oversight (e.g. restrictions on land use, environmental monitoring programmes, archived records and site markers). While the probability of inadvertent human intrusion at a specific site is unknowable as it is based on future human actions, it is assumed that it could occur after the period of indirect control, but the radiological impact should not be severe due to the limitations placed on the disposed inventory of waste.

(127) When assessing the radiological consequences of inadvertent human intrusion, it is challenging to fully characterise inadvertent human intrusion events. Judgement is needed in deciding reasonable intrusion scenarios and similar to the approach in determining the characteristics of the representative person, extreme practices should not be adopted. Since there is limited scientific basis for predicting the nature or probability of future human actions and also because, by definition, an intrusion event bypasses some or all of the barriers that have been put in place, the consequences of one or more plausible generic or stylised intrusion scenarios should be considered by decision makers to evaluate (1) the resilience of the disposal system to potential inadvertent human intrusion, and (2) what constitutes an acceptable level of residual activity in the disposal facility.

(128) Due to the challenges in establishing the probability of inadvertent human intrusion, the Commission considers it prudent to assume intrusion will occur, corresponding to an

existing exposure situation. As such, reference levels in the lower half of the 1 mSv to 20 mSv per year band would be applied with the objective to progressively reduce exposure to levels towards the lower end of the band is recommended for off-site impacts. In addition, doses to environmental biota should be compared to the appropriate DCRLs. It should be noted that the optimum design of a disposal system may result in a distribution of doses from inadvertent human intrusion where some could be predicted to be above these reference levels. While establishing a single specific probability of inadvertent human intrusion is not possible, aspects of understanding the likelihood, such as, current human activities in the area or depth of the disposal facility, may be used to inform what generic or stylized intrusion scenarios are appropriate or can be used in the optimisation process, when evaluating alternative disposal system approaches.

5. CONCLUSIONS

(129) This report describes and clarifies the application of the Commission's recommendations for the protection of the public and workers (*Publications 101* & *103*) as well as the environment (*Publication 124*) as applicable to surface and near-surface disposal of radioactive waste. It is complementary to *Publication 122* that deals with radiological protection for the geological disposal of long-lived radioactive waste.

(130) There are many types of solid radioactive waste that are potentially suitable for disposal in a near-surface facility with a wide range of radiological and physical properties from a variety of industries and human activities. Regardless of their source and properties, the protection of workers, the public and the environment needs to be demonstrated, assured and optimised. In addition to the actual disposal facility, the waste management system as a whole should be considered because choices made in the processes before disposal may influence the disposal option.

(131) Near-surface disposal facilities are intended to provide the degree of containment and isolation needed for time scales over which the waste presents a significant radiation hazard. For short-lived radionuclides, this will be a period of several hundred years. For longer-lived radionuclides, this timeframe will be longer, but restrictions on the inventory in the disposed waste will limit the longer-term residual risk. Containment and isolation are provided by physical barriers and to help ensure their ongoing integrity measures such as institutional control of access to the disposal site and restrictions on the use of the land associated with the site are important. Site selection is such that severely disrupting events are avoided to the extent possible as well as the likelihood of inadvertent human intrusion reduced to the extent practicable. A safety case must demonstrate the suitability of the disposal facility for the waste intended to be disposed. This is achieved in part by providing containment and isolation for as long as necessary, with limited exposure to workers, the public and the environment.

(132) Waste can come from all types of exposure situations and once the management of waste starts, the associated activities are best described as a planned exposure situation, although some situations maybe more nuanced. While the deliberate introduction of the near-surface disposal facility is considered a planned exposure situation, exposures from the facility are not planned to occur as such. The aim of disposal of radioactive waste is to avoid and/or reduce exposures to the extent possible, both in the operational phase (waste emplacement and closure) and in the post-closure phase when the facility is closed and is functioning as a passive system. Consideration also needs to be given with more disruptive events (e.g. intrusion) that may result in an emergency or existing situation.

(133) The ICRP system of radiological protection builds on the three principles of justification, optimisation and dose limitation. Their successful implementation requires consideration of the core ethical values such that the disposal of radioactive waste should result in a benefit and avoid harm (beneficence/non-maleficence), unnecessary risk being avoided (prudence), avoiding unfair distribution of risk (justice) and people being treated with respect (dignity).

(134) For a near-surface disposal system optimisation of protection has to deal with the protection of people and the environment during the operational period and protection of future generations and the environment beyond closure of the facility including a time when it is assumed that there is no oversight over the facility. In the long term and particularly when no active oversight is in place, radiological protection has to be ensured by a passively functioning disposal system. Optimisation of protection has to consider the balance between

passive and active measures of safety, for example, when deciding on the foreseen duration and nature of institutional control measures.

(135) Balancing the many factors necessary to optimise the radiological protection of the facility will require prudent decisions to be made, sometimes with incomplete knowledge (e.g. the long-term environmental conditions, possible inadvertent human intrusion scenarios, etc.). Prudence is required to ensure an undue burden is not imposed on the current or future generations. This naturally raises the issue of distributive justice and also the dignity of the current and future generations. Near-surface disposal facilities need to be designed and operated in a manner that provides a high-level of assurance of adequate protection to all members of both present and future generations and the environment.

(136) The implementation and integration of the procedural ethical values of accountability, transparency, and stakeholder participation throughout the project should help the regulatory authority and the stakeholders have confidence in the long-term performance of the facility for controlling release and migration of radionuclides from the facility and meeting the radiological protection criteria.

(137) As a facility transitions from the operational phase to the post-closure phase a designated authority may control land use and may also carry out periodic inspection of the site to ensure conditions assumed in the post-closure safety case remain valid. It must also be assumed that at some time in the future control of the facility may cease, which means it is important to maintain oversight until confidence that the criteria for the long-term performance, including those for inadvertent human intrusion, are satisfied.

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GLOSSARY

Best Available Techniques (BAT)

The most effective and advanced available techniques that will establish and maintain the long-term robustness and integrity of the facility.

Biosphere

That part of the 'environment' normally inhabited by living organisms. In practice, the 'biosphere' is not usually defined with great precision, but is generally taken to include the atmosphere and the Earth's surface, including the soil and surface water bodies, seas and oceans and their sediments. There is no generally accepted definition of the depth below the surface at which soil or sediment ceases to be part of the 'biosphere', but this might typically be taken to be the depth affected by basic human activities, in particular, farming. In the 'safety' of 'radioactive waste management', in particular, the 'biosphere' is normally distinguished from the 'geosphere'.

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Disused sealed source

A radioactive source, comprising radioactive material that is permanently sealed in a capsule or closely bonded and in a solid form (excluding reactor fuel elements), that is no longer used, and is not intended to be used, for the practice for which an authorization was granted. (IAEA glossary)

Exposure situation

A situation where a natural or man-made radiation source, through various pathways, results in exposure of humans or non-human biota in the environment.

Human Intrusion

Those actions by humans that result in the direct disturbance of the actual disposal facility (e.g. the waste or the engineered barriers).

Safety case

A safety case is a structured set of arguments and evidence demonstrating the safety of a system. More specifically, a safety case aims to show that specific targets and criteria are met with the goal of providing protection of humans and the environment from the hazards of radiation.

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