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Radiological Protection in Geological Disposal of Long-Lived Solid Radioactive Waste

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Abstract –This report updates and consolidates previous recommendations of ICRP related to solid waste disposal (Publications 46, 77, 81). The recommendations given in this report apply specifically to geological disposal of long-lived solid radioactive waste. The report explains how the 2007 ICRP System of Radiological Protection described in ICRP Publication 103 can be applied in the context of the geological disposal of long-lived solid radioactive waste. The report is written as a self standing document.

The 2007 ICRP System of Radiological Protection maintains the Commission's three fundamental principles of radiological protection namely justification, optimisation, and the application of dose limits. The Recommendations evolve from the previous process-based protection approach using practices and interventions by moving to an approach based on the exposure situation. They maintain the Commission's current individual dose limits for effective dose and equivalent dose from all regulated sources in planned exposure situations. They re-enforce the principle of the optimisation of radiological protection. The Recommendations also include an approach for developing a framework to demonstrate radiological protection of the environment.

This report describes the different stages in the lifetime of a geological disposal facility and addresses the application of relevant radiological protection principles for each stage depending on the various exposure situations that can be encountered. In particular, the crucial factor that influences the application of the protection system over the different phases in the lifetime of a disposal facility is the level of oversight that is present. The level of oversight affects the capability to reduce or avoid exposures. Three main timeframes have to be considered for the purpose of radiological protection: time of direct oversight when the disposal facility is being implemented and active oversight is taking place; time of indirect oversight when the disposal facility is sealed and indirect oversight is being exercised to provide additional assurance on behalf of the society; time of no oversight when oversight is no longer exercised because memory is lost.

Keywords: Geological disposal, Radioactive waste, Protecting future generations

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Preface

On February 12, 2010, the Main Commission of the International Commission on Radiological Protection (ICRP) approved the formation of a new Task Group, reporting to Committee 4, to develop a report which describes in plain language how the recommendations given in ICRP Publication 103 can be applied in the context of the geological disposal of long-lived solid radioactive waste. The report covers both the protection of humans (workers and the public) and the environment and discusses key issues like the transition from a planned to an existing exposure situation in case of a loss of control of the waste system as well as the applicability of dose calculated for the far future for decision aiding. The report updates ICRP Publication 81.

The report provides guidance on:

- the basic concepts and terms, eg. the radiation protection principles, the different types of situations (including human actions), dose and risk constraints;
- the nature and role of optimization (stepwise approach, short term vs. long term, best available technology);
- the use and application of dosimetric units and concepts (dose and risk constraints, potential exposures, collective dose, different time frames);
- the role of stakeholder involvement in different stages of planning and development.

The membership of the Task Group was as follows:

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The corresponding members were:

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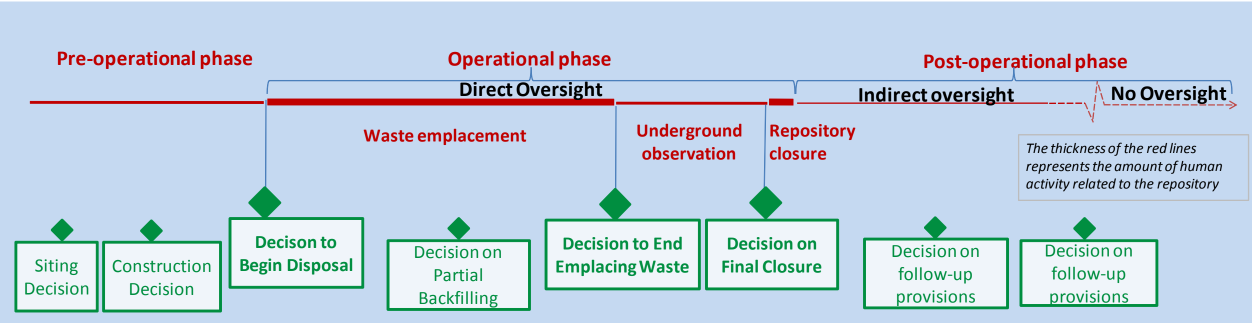
The Task Group wishes to thank those organizations and staff that made facilities and support available for its meetings. These include BfS, ARPANSA, NRC, NIRAS, HPA, CEPN, JAEA, EC, OECD/NEA, IAEA.

The report was approved by the Commission in XX in 2011.

Executive summary

(a) This report provides advice on the application of the Commission's 2007 Recommendations (ICRP Publication 103) for the protection of humans and the environment against any harm that may result from the geological disposal of long-lived solid radioactive waste. It illustrates how the key protection concepts and principles of ICRP Publication 103 are to be interpreted and how they apply over the different timeframes over which a geological disposal facility for long-lived solid radioactive waste would have to provide radiological protection (see Figure).



(b) The goal of a geological disposal facility is to isolate and contain the waste in order to protect humans and the environment for time scales that are comparable with geological time scales. At great distance from the surface, changes are particularly slow. With distance from the surface, and having chosen appropriate sites the potential for human intrusion will be limited. Radioactivity will decrease with time, and any release would be slowed down and diluted further by a properly chosen geological formation. Geological disposal is recognized by the international organisations as especially intended for high level radioactive waste or spent fuel where long term isolation and containment is required. Geological disposal may also be used for other long-lived wastes since a similar need for long term protection applies.

(c) The design of a geological disposal facility addresses a series of developments with different probabilities that may be defined by regulation. Besides these design-basis developments, the developer / implementer and the regulator may want to assess evolutions in non-design-basis conditions in order to judge the robustness of the system.

(d) These ICRP recommendations describe the radiological concepts and criteria that ought to be used by both the designer and/or operator of the facility and the regulator. For the assessment of the safety and radiological protection of a geological disposal facility for long-lived radioactive waste various dose and risk constraints are used. Optimisation deals with the main aim of a disposal system, i.e., the radiological protection of humans and the environment. Optimisation of protection is the central element of the step-wise construction and implementation of a geological disposal facility. It has to cover all elements of the system, including the societal component, in an integrated way. Important aspects of optimisation of protection must occur prior to waste emplacement, largely during the siting and design phase. The optimisation efforts can be informed by, and construction supplemented with, consideration of best available technique (BAT) as applied to all stages of disposal facility siting and design. During the implementation phase, some further optimisation is possible but very little can be done to further optimise the performance of the engineered features after waste emplacement has occurred. In the long term optimisation of protection can only be achieved if oversight is maintained.

(e) In the distant future the geological disposal facility might give rise to some releases to the accessible environment and the “safety case” has to demonstrate that such releases, should they occur, are compatible with regulation and radiological protection criteria. In application of the optimisation principle, the reference radiological impact criterion for the design of a waste disposal facility recommended by ICRP is an annual dose constraint for the population of 0.3 mSv in a year [ICRP 103], without any weighting of doses in the far future. For less likely events resulting in potential exposures, the Commission continues to recommend a risk[1] constraint for the population of $1\ 10^{-5}$ per year. However, ICRP Publication 103 also warns that, given the long timeframes considered in waste disposal, the evolution of society, human habits and characteristics is such that effective dose looses its direct connection to health detriment after the time span of a few generations. At the same time, in the distant future, the geosphere and the engineered system and, even more, the biosphere will evolve in a less predictable way. The scientific basis for dose and risk assessments at very long times into the future then becomes questionable and the strict application of numerical criteria may be inappropriate. Hence, the annual dose constraint of 0.3 mSv in a year is to be used for the sake of comparison of options rather than as means of assessing health detriment.

(f) In particular, a crucial factor that influences the application of the protection system over the different phases during the lifetime of a geological disposal facility, is the level of oversight that is present. The level of oversight directly affects the capability to reduce or avoid some exposures. Three main timeframes have to be considered: the time of direct oversight when the disposal facility is being implemented and active oversight is taking place (operational phase); the time of indirect oversight when the disposal facility is partly (backfilling and sealing of drifts) or fully sealed (post-closure period) where direct regulatory oversight might be supplemented or replaced by institutional oversight (e.g. restriction of land use) and the time of absence of oversight (post-closure period in distant future) in case memory is lost, although the primary objective is to keep memory of the site.

(g) The exposures arising from the design basis evolution of the geological disposal facility are planned exposure situations as defined in ICRP Publication 103. They include potential exposures from events with low probability which have to be considered as part of the design basis. If severe disturbing events outside the design basis occur while there is still oversight (direct or indirect) of the disposal facility and which result in doses largely exceeding 0.3 mSv in a year, the ensuing situation will be considered as an emergency exposure situation followed by an existing exposure situation in case this emergency is resulting in a long lasting contamination of the environment. If a severe disturbing event occurs when there is no longer any oversight of the disposal facility, there is no certainty that a competent authority would be able to understand what is the source of the exposure and therefore, it is

[1] Risk is used in this document always to mean **radiological risk** as defined in ICRP Publication 103.

not possible to consider with certainty the implementation of relevant countermeasures to control the source. However, there is a need to evaluate the consequences within the scope of an existing exposure situation.

(h) For the "design basis" evolution, the dosimetric criteria relevant to planned exposure situations will be considered for assessing the safety and robustness of the disposal facility. For a severe disturbing event, the reference level to be considered for emergency exposure situation would apply when relevant (i.e. reference level in the range of 20 to 100 mSv for the first year). It is also necessary to evaluate the possible consequences of the occurrence of such events on the basis of the dosimetric criteria relevant for existing exposure situation as defined by ICRP (i.e. reference level of a few mSv per year).

(i) The safety case of a geological disposal facility, by including events that are not expected to occur with high certainty, includes automatically considerations on how to deal with potential exposures as defined by ICRP Publication 103 (section 6.1.3).

(j) ICRP recommends that dose or risk estimates derived from these exposure assessments should not be regarded as direct measures of health effects beyond timescales of around several hundred years into the future. Rather, they represent indicators of the protection afforded by the geological disposal system.

(k) The application of the three exposure situations and of dose limits, constraints and reference levels as defined in ICRP Publication 103 during these timeframes is indicated in Table 1.

RADIOLOGICAL EXPOSURE SITUATIONS AS FUNCTION OF DISPOSAL FACILITY EVOLUTION AND PRESENCE AND TYPE OF OVERSIGHT			
Disposal facility Status	**Type of Oversight**		
	Direct Oversight	**Indirect Oversight**	**No oversight**
Design-basis[1] evolution	Planned Exposure Situation[2]	Planned Exposure Situation[2]	Planned Exposure Situation[2,3]
Non-design basis evolution involving significant exposures to people and the environment	Emergency Exposure Situation at the time of exposure, followed by an Existing Exposure Situation[4]	Emergency Exposure Situation at the time of exposure, followed by an Existing Exposure Situation[4]	Emergency and/or Existing Exposure Situation
Inadvertent Human Intrusion	not relevant	not relevant	Emergency and/or Existing Exposure Situation

[1] The design basis is the envelope of both expected and less likely (potential) events that are used in planning the facility.

[2] At design: 20 mSv in a year dose limit to worker and dose constraint to be specified by operators; 1 mSv in a year dose limit and 0.3 mSv in a year dose constraint for the public, in the case of less likely events within the design basis a risk constraint of $1\ 10^{-5}$ per year for the public is suggested.

[3] No worker dose is foreseen during the period of no oversight

[4] For an emergency exposure situation a reference level between 20 and 100 mSv per year is recommended; for an exisiting exposure situation a reference level should be selected in the lower part of the band between 1 and 20 mSv per year, eg., in the range of a few mSv per year.

1. Introduction

(1) In the context of the Commission's recommendations, waste is any material for which no further use is foreseen. Waste, as generated, includes liquid and gaseous effluents as well as solid materials. Waste storage is the temporary retention of waste. Waste disposal is the permanent isolation and containment of waste in an appropriate facility. Waste management means the whole sequence of operations starting with the generation of waste and ending with disposal.

(2) This report deals with geological disposal of long-lived solid radioactive waste which is intended to isolate and contain especially high level waste, spent fuel and intermediate level wastes containing radionuclides with long half lives. These are concentrated wastes which contain high specific activities; they need to be handled remotely, for hundreds or thousands of years. The report does not address near surface disposal facilities because they differ from geologic disposal facilities in two key aspects: the isolation and containment function and the waste for which they are intended.

(3) Technical solutions for the permanent isolation of long-lived, solid radioactive waste at distances from the surface of hundreds of metres in geological formations are being developed and pursued in a number of countries. Geological disposal is currently recognized by international organisations in charge of radioactive waste management as especially suited for high level radioactive waste or spent fuel where long term containment is required. Geological disposal may also be used for other wastes containing long lived radionuclides since similar long-term protection requirements can be formulated. An example of geological disposal is the emplacement of waste in excavated tunnels or shafts, followed by backfilling and sealing of the entire facility.

(4) The goal of a geological disposal facility is to achieve the isolation and containment of the waste and to protect humans and the environment for time scales that are comparable with geological changes. At great distance from the surface, such changes are particularly slow and, at the same time, radioactivity will decrease with time. Additionally, if a site is chosen in an area with no known natural resources, the potential for human intrusion will be limited. Finally, a properly chosen geological formation would assure stable chemical conditions for the waste. Further, it would attenuate and slow down any releases of radionuclides. In this context ‘distance’ can imply horizontal or vertical distance as, for example the case of a disposal facility sited deep within a mountain.

(5) The safety strategy implemented for geological disposal is that to concentrate and retain the waste. No exposure is ever intended, although these may happen. The disposal facility is thus to be seen as a functional facility whose controls are in-built and whose safety, after facility closure, does not rely on the presence of man. The safety function to be fulfilled by a geological disposal facility independent of man is to isolate and contain the waste over as long a period of time as possible. This will allow radioactive decay to take place and attenuate and delay the eventual release of any contaminants to the accessible environment. Furthermore, it will reduce the risk of inadvertent human intrusion. In the situation of a human intrusion the health

consequences for the intruder might be high. But this is an inescapable consequence of the decision to concentrate waste in a disposal facility.

(6) Geological disposal of long-lived solid radioactive waste poses a number of challenges related to radiological protection over extended periods of time, e.g. the nature and role of optimization of protection during the various phases of the development and implementation of the disposal facility and the applicability of dose and risk calculated for the far future for decision aiding. The report explains how the protection principles as laid out in ICRP Publication 103 can be applied under these circumstances. It also considers elements that can assist in demonstration of compliance with the protection principles and how the principles, in broad terms, relate to other protective goals that would be considered in an environmental impact assessment/statement.

(7) Radiological protection is only one set of the protection concepts that will be used by safety analysts in documenting the protection capability of the disposal facility. Other concepts may relate to the protection of resources in a sustainable way such as for example groundwater as a drinking water resource. The chemical toxicity of the waste or the waste containment system in a disposal facility for radioactive waste may be a further issue of concern. Optimal protection would be achieved by the application of an integrated framework of protection concepts in which the level of protection of humans, the environment and the resources are comparable for radiotoxic and chemotoxic substances.

(8) The Commission has previously published protection recommendations for the disposal of long-lived radioactive waste (ICRP Publications 46, 77, 81) consistent with its general recommendations for the application of its overall System of Radiological Protection (ICRP Publication 60). More recently, the Commission has published new general recommendations (ICRP Publication 103). This report summarizes and explains how these recommendations specifically apply to a geological disposal facility for long-lived solid radioactive waste.

(9) This report is written as a stand-alone presentation of the Commission's Publication 103 system of radiological protection as it should be applied in the context of geological disposal of long-lived radioactive waste. It covers all issues related to radiological protection of humans and the environment against harm that may result from the geological disposal of long-lived solid radioactive waste. Where the Commission’s recommendations are unchanged, or issues are addressed sufficiently in publications by other international organisations, references are given and no detailed discussion is provided.

(10) In the case of geological disposal, the occupational exposure of workers and the exposure of the public are managed in accordance with the ICRP system of protection. The main protection issue dealt with in this report concerns exposures that may or may not occur in the far future. Any corresponding estimates of doses to individuals and populations will have growing associated uncertainties as a function of time due to incomplete knowledge of the future disposal system behaviour, of geological and biospheric conditions, and of human habits and characteristics. Furthermore, due to the long timescales, verification that protection is being achieved

cannot be expected in the same manner as for current discharges since knowledge of the disposal facility may eventually be lost and oversight may be absent. Neither can it be assumed that effective mitigation measures will necessarily be carried out, should they be required in the far future. Nevertheless, the Commission's system of protection can be applied to the disposal of long lived solid radioactive waste, with due interpretation.

1.1 References

ICRP (1985) Protection Principles for the Disposal of Solid Radioactive Waste. ICRP Publication 46, Annals of the ICRP 15 (4).

ICRP (1991) 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Annals of the ICRP 21 (1–3).

ICRP (1997) Radiological Protection Policy for the Disposal of Radioactive Waste. ICRP Publication 77, Annals of the ICRP 27 Supplement 1997.

ICRP (1998) protection recommendations as applied to the disposal of long-lived solid radioactive waste. ICRP Publication 81, Annals of the ICRP 28 (4).

ICRP (2007). The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103, Annals of the ICRP 37 (2–4).

2. Scope of this report

(11) This report deals with the radiological protection of workers, members of the public and the environment, following the disposal of long-lived solid radioactive waste in geological disposal facilities. The recommendations given in this report apply to disposal facilities where there is still an opportunity for their implementation during the site selection, design, construction, and operational phases. They should also be taken into account in the justification of decisions involving practices generating waste.

(12) The report does not describe the disposal safety assessment in detail. It rather provides a description of how protection criteria can be used in the safety analysis, and establishes recommendations on protection issues related to the disposal of long-lived solid radioactive waste. Exposures are estimated in order to place adequate control on the source of exposure. The characteristics and habits of exposed individuals and populations are taken into account.

(13) The report does not address near surface facilities because they differ from geological facilities with respect to the isolation function and the waste for which they are intended. Near surface facilities principally rely on the engineering containment provided by the facility and on the presence of man. The long term stability of the surrounding soil or rock and its attenuation properties are of secondary importance. Also, they are by definition more easily accessible and hence a near surface facility can only provide short term isolation of the waste. Near surface facilities are suitable for low and intermediate level wastes containing predominantly shorter lived and less concentrated levels of radionuclides. The differences in the functions of near surface facilities and geological facilities, together with the different wastes they receive, result in the application of specific regulatory regimes: one for near surface disposal and one for geological disposal. Previous ICRP recommendations for the radiological

protection of workers, members of the public and the environment in the case of near surface disposal facilities or other disposal options are still valid.

3. Basic values and goals underlying protection for a geological disposal of radioactive waste

3.1 Values underlying the ICRP principles for protecting future generations

3.1.1 Basic values for the protection of future generations

(14) The initial composition of radionuclides contained into long lived radioactive waste evolves over time, changing the nature of the hazard. At the same time, even though the activity decreases with time, the halflife of some radionuclides, and the rate of ingrowth of others, are such that some of these wastes may never be considered as not being a hazard.

(15) Over the last decade, reflections on safety and societal issues associated with this long-term dimension clearly point out the complexity of the situation: on one hand it is not possible to envisage how the society will be organized in the far future while on the other hand the current generation has to take care of the possible future in order to design the waste management strategy. This is notably the core of the ethical reflections regarding the precautionary principle and sustainable development, in order to preserve the resources and the environment for the future generations.

(16) The 1997 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management details the long-term aspects of the safety objectives for disposal by requiring to meet the principle that "…individuals, society and the environment are protected from harmful effects of ionising, now and in the future, in such a way that the needs and aspirations of the present generation are met without compromising the ability of future generations to meet their needs and aspirations" (IAEA 1997). In a broad sense this principle is consistent with one of the recommendations of ICRP Publication 77: "the Commission recommendations rely on the basic principle that individuals and populations in the future should be afforded at least the same level of protection as the current generation." These recommendations were further expanded and clarified in ICRP Publication 81 (paragraphs 41 and 42).

(17) In the same vein, the obligations of the present generation toward the future are complex, involving, for instance, not only issues of safety and protection but also of transfer of knowledge and resources. Due to the technical and scientific uncertainties and to the evolution of society in the long-term, it is generally acknowledged that the capacity of the present generation to guarantee delivery of its obligations diminishes with distance in time.

3.1.2 Basic ICRP principles dealing with future generations

(18) The main strength of ICRP consists in its unified protection system applicable to all types of exposure situations. In its 2007 Recommendations (ICRP Publication 103), the ICRP protection system continues to rely on its three fundamental principles: justification, optimisation of protection and application of dose limits, applied according to the exposure situation considered.

(19) The optimisation principle is of primary importance and its role has been reinforced in the new ICRP Recommendations. 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 Publication 103, paragraph 203).

(20) For this assessment, two concepts are considered by ICRP: dose and risk. Associated with dose and risk, the concept of health detriment, as introduced by ICRP in its Publication 26, is also a key concept to consider for assessing the level of protection. The application of this concept aims at providing an estimate of the total harm to health to individuals and their descendants as a result of an exposure, assuming a linear-non-threshold dose-effect relationship. For exposures that may occur in the long-term, the relevance and meaning of dose and risk is of interest and their interpretation over the different time periods has to be clarified. It should be noted that the knowledge of the relationship between dose and effect may very well change in the future, as has already been demonstrated by past reassessments of nominal probability coefficients. Likewise, the ability to cure or mitigate induced health effects may change in the future. It is not possible to make any prediction of the direction of these changes. Thus, the efforts to avoid and/or reduce any effect on human health and on the environment in the far future have to be entirely guided by the current understanding of health and environmental effects.

(21) Notwithstanding the uncertainty described above, the ICRP dosimetric quantities and the health detriment can be used for long-term assessment. In fact, the assessment of the robustness of the protection system provided by solid waste disposal in the long-term does not need a precise knowledge of the evolution of the general health of the population in the far future. At the design stage, what is at stake is not to evaluate what would be the level of health effects in a group of population in the far future. The challenge is rather to estimate, in an optimisation process through a comparison (using dose and risk indicators) of alternative options, the levels of protection achieved by a given disposal facility system and to judge if the estimated protection level of the chosen strategy is acceptable in the light of the level of protection accepted today.

3.2 Geological disposal: Objective and Implementation steps

3.2.1 Strategies for the management of long-lived solid radioactive waste

(22) Because of the nature and longevity of hazards, the fundamental strategy adopted for the management of long-lived radioactive waste in order to achieve the safety objective is to concentrate and contain the wastes and to isolate them from the environment as long as possible. The goal of a geological disposal facility is to provide protection of humans and the environment from the hazards that the radioactive waste and the waste containment system would pose over time. The current generation has to take care of the possible future developments when designing the waste management strategy. These possible developments imply different timescales with different levels of presence of human institutions but also

uncertainty concerning the level of presence of humans themselves.

(23) It is internationally recognized that only materials that have been declared as having no further use for society (waste) are disposed of, so that there is no intention by the current generation to retrieve it, even if technical options to do that were available. Disposal is not to be confused with a storage situation. Currently, the reference option is to dispose of these wastes in engineered deposition facilities located in suitable geological formations [IAEA 1997, OECD-NEA 2008].

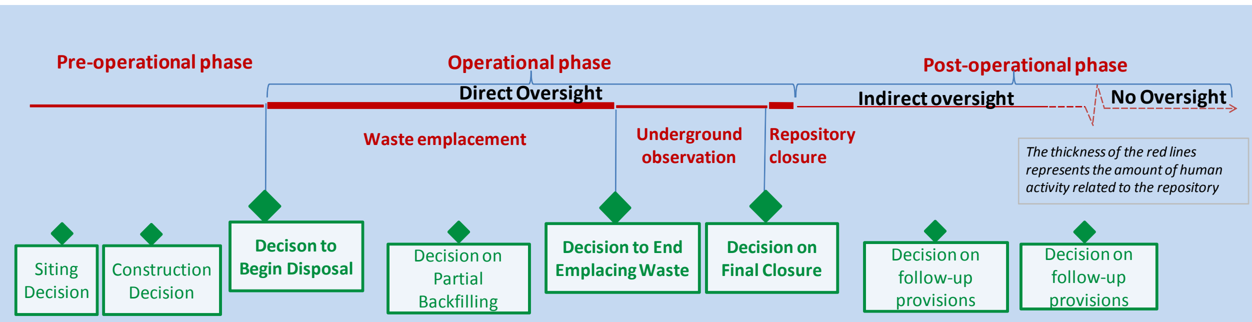
(24) A step-wise process, involving various stakeholders, is considered as a responsible approach to planning for the disposal development and implementation, including final closure. In that context the concepts of reversibility and retrievability into the disposal facility programmes are also considered. Reversibility implies a disposal programme that is implemented in stages, keeps options open at each stage, and provides the capacity to manage the disposal facility with flexibility over time. Retrievability is the possibility to reverse the step of waste emplacement during the entire operational phase, e.g. before final closure of the disposal facility. Retrievability does not imply the intention to retrieve nor is retrieval a contingency plan for the disposal facility. The key is to consider any choices that could facilitate retrieval if this was ever required but to continue to ensure that the integrity of the facility is not jeopardised by these choices. The decision to actually carry out any retrieval would be a separate decision taken in the future, according to the radiological principles that apply to a new planned activity.

(25) The “concentrate and contain” strategy makes it possible, in principle, for the waste to be re-accessed either voluntarily or involuntarily at some time in the future. Therefore, disposal systems ought to be designed to reduce the possibility of inadvertent or malevolent events. There are to some extent conflicting requirements involved and a balance has to be found in each case, taking into consideration the timescales, the nature of the waste, the nature of the host geological formation, and the evolving desires of society.

3.2.2 Life phases of a disposal facility and the safety analysis process

(26) With respect to the presence of man for managing the facility, the development of a geological disposal facility involves three main phases (Fig. 1) whose durations vary amongst national programmes depending on the design and on each country’s approach to decision making.

Fig. 1 **Disposal facility life phases and relevant oversight periods**



(27) The **pre-operational phase**: During this phase, the disposal facility is designed, the site is selected and characterized, the man-made materials are tested and the engineering demonstrated, safety cases for operational and post-operational phases are developed, the licenses for building and operation are applied for and received, and construction begins. A baseline of environmental conditions is also performed.

(28) The **operational phase:** During this phase, the emplacement of waste is performed, followed by a period of observation prior to the closure. At one time during this phase, some galleries will be filled and sealed and will have thus reached their final configuration, while others will still be excavated.

This phase will be under **direct oversight** of the safety authorities in cooperation with other relevant stakeholders and it may be divided into three relevant time periods:

- ***The emplacement period***: A licence is granted that authorizes the transfer and emplacement of waste packages to underground in pre-excavated galleries, rooms, and/or boreholes. The environmental conditions are continuously monitored and compared to the baseline data. Research and development continues. The regulator performs regular inspections of the underground operations. The long-term safety case is regularly updated and reviewed by the regulator. In this phase, new underground galleries may be built and partial backfilling and/or sealing of galleries and disposal facility areas may also take place.
- ***The observation period***: After all waste packages are emplaced it might be decided to monitor (parts of) the disposal facility and to keep some accessibility to at least part of the waste while additional performance confirmation takes place.
- ***The closure period:*** A license to close is granted and access from the surface to the underground facility is terminated. Backfilling and sealing are performed according to design. Surface facilities may be dismantled. The archives of all relevant information are to be provided for long-term preservation.

(29) The **post-operational phase**: during this phase the presence of man is no longer required to directly manage the facility. This phase is the longest one, and is divided into two relevant time periods:

- The **period of indirect oversight**: After closure, safety is assured totally through the intrinsic, built-in provisions of the design of the disposal facility. Nevertheless, it is expected to continue monitoring of the baseline environmental conditions including some remote monitoring. Archives on technical data and configuration of waste packages and the disposal facility will be kept, as well as markers to remind coming generations of its existence. The relevant international safeguards controls continue to apply. Inadvertent human intrusion in the disposal facility can be ruled out.
- The **period of no oversight**: Although termination of indirect oversight is not foreseen, it will still have to be considered in the design and planning stage as there is no guarantee that it will be maintained as well as the memory of the

site in the distant future. Eventually, loss of oversight and memory may take place, either progressively or following major unpredictable events such as war or loss of records. Therefore, inadvertent human intrusion in the disposal facility cannot be ruled out during this time period. The intrinsic hazard of the waste will decrease with time but it may continue to pose a significant hazard for a considerable time. The loss of oversight does not result in a change of the protection capability of the disposal facility.

(30) As long as oversight is effective, it will be possible to evaluate the protection capability of the disposal facility based on regular updates of the safety case. The safety case provided by the developer of a disposal facility must address the operational and the post-operational phase and, specifically the distant future, when controls and interventions cannot be relied upon. The aim of the developed safety case is to provide convincing evidence of the intrinsic protective capability of the system. The safety case shows how the barriers in the disposal facility system work together and how they fulfil their desired functions over time. It documents the principles and strategies that were followed for developing the knowledge base. It recognises the residual uncertainties in both the long-term processes and potential future events that may affect the performance of the disposal facility and why these have been considered as not to reduce protection unduly. Interactions with the various stakeholders - e.g., the local public, outside experts brought in to conduct independent reviews - are acknowledged elements to enhance the quality of the decision-making process at the different phases of the disposal facility development and implementation.

3.2.3 Relevant timeframes for radiological protection

(31) As stated before, the scope of this ICRP report is the description of how protection criteria can be used in the safety assessment, and to establish recommendations on protection issues related to the disposal of long-lived solid radioactive waste. One of the crucial factors that influences the application of the protection system over the different phases in the lifetime of a disposal facility is the level of oversight that is present. The level of oversight will directly affect the capability to reduce or avoid some exposures. Three main timeframes have to be considered:

- **Time of direct oversight:** when the disposal facility is being implemented and active oversight is taking place. This timeframe coincides with the pre-operational and operational phases of the disposal facility;
- **Time of indirect oversight:** when the disposal facility is sealed and indirect oversight is being exercised to provide additional assurance on behalf of the society. This timeframe coincide with the post-operational phase of the disposal facility.
- **Time of no oversight:** when oversight is no longer exercised because memory is lost. This timeframe coincides with the post-closure period in the distant future.

The transition between the different timeframes has also to be considered

(32). During the time of direct oversight both the operator and the regulator in interaction with the concerned stakeholders will be able to actively manage the protection of workers, the public and the environment through direct and indirect actions. The transition from this timeframe into the timeframe of indirect oversight is not abrupt. Thus parts of the disposal facility will be under direct oversight, and at the same time others will be under indirect oversight.

(33) During the time of indirect oversight, there might be some presence of people/staff/operator at the site. Knowledge is maintained, monitoring may continue to occur and some corrective actions could be made if needed. However, in most cases, options to address radiological protection will be indirect. As time progresses the degree of oversight may change, corresponding, for example, to less frequent inspections. The decisions to reduce the level of oversight would be based to some extent on the degree of confidence in the behavior of the facility, and other societal and economic factors. Decisions related to the organization and evolution of the oversight should be discussed with the stakeholders concerned.

(34) It is to be expected that regulators and society will maintain forms of oversight and memory as long as possible. However, there is no guarantee on there existence in the distant future. At this point the facility implicitly leaves the regulatory regime.

(35) No matter in which way oversight ceases to exist, the disposal facility is still a functioning facility and continues to be so. The potential to isolate and contain the radioactive waste is an inherent feature of the radioactive waste disposal facility that continues into the far future and responds to the considered evolution of the disposal facility under natural processes and events. The multi-barrier, multi-function system that is at the basis of the disposal facility design must have the potential to constrain releases of radionuclides from the radioactive waste disposal facility.

(36) Another type of passive control that may continue after the direct oversight ceases is provided by memory or records of the presence of a geological disposal facility or other measures decided by the authorities in interaction with the different stakeholders, however for a much shorter timescale. This reduces the probability of direct inadvertent intrusion by people into the facility and it may assist in the justification and planning for any advertent intrusion, if desired. At some point in the distant future, the memory of the presence of the disposal facility may be lost and there is no defense mechanism against direct inadvertent intrusion, apart from the fact that the waste is out of sight and stored at great distance from the part of the biosphere that people normally inhabit. The location of the geological disposal facility and its technical design will constitute the remaining built-in “control” against inadvertent intrusion.

(37) The cessation of direct oversight of the site will not occur before tens to hundreds of years after the start of operations. It is not possible to specify the criteria that will be used by the people making decisions at that time. The different decisions to be made related to the evolution of the oversight should be discussed with the stakeholders.

(38) As such, the assumption that cessation of indirect oversight will occur does not correspond to a regulatory decision to release radioactive materials from regulatory control.

4. Application of the ICRP system of protection during different timeframes in the life of a geological disposal facility

(39) The major features of the 2007 ICRP Recommendations (ICRP Publication 103) relevant to this report are:

- Maintaining the Commission's three fundamental principles of radiological protection, namely justification, optimisation, and the application of dose limits, and clarifying how they apply to sources delivering exposure and to individuals receiving exposure.
- Evolving from the previous process-based protection approach using practices and interventions, by moving to a situation-based approach applying the fundamental principles of justification and optimisation of protection to all controllable exposure situations, which the 2007 ICRP Recommendations characterise as planned, emergency, and existing exposure situations.
- Re-enforcing the principle of optimisation of protection, which should be applied in a similar way to all exposure situations, with restrictions on individual doses and risks, namely dose and risk constraints for planned exposure situations and reference levels for emergency and existing exposure situations.

4.1 The application of the principles "justification", "limitation" and "optimisation"

(40) The definitions of the three basic principles and basic considerations for their application to waste disposal are described as follows.

- The Principle of Justification: "*Any decision that alters the exposure situation should do more good than harm.*"
  Waste management and disposal operations are an integral part of the practice generating the waste. It is wrong to regard them as a free standing practice that needs its own justification. The waste management and disposal operations should therefore be included in the assessment of the justification of the practice generating the waste (ICRP 77 §34). This assessment should include considerations of different options for waste management and disposal including the justification of these options. If the national waste disposal policy has changed and the practice is continuing, it may be necessary to reassess the justification of the practice. If the practice has ceased, the protection strategy, rather than the practice, has to be considered for justification.

- The Principle of Optimisation of Protection: *"The likelihood of incurring exposure, 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."*
  As clearly stated in ICRP Publication 103, optimisation is of primary importance and its role has been reinforced. This is also the key principle guiding the application of the ICRP system of protection in the disposal of long-lived solid radioactive waste, as discussed in this report (for details see section 4.4).

- The Principle of Application of Dose Limits: *"The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits specified by the Commission."*
  The general statement of ICRP Publication 81 (paragraph 36) still applies: "Although the Commission continues to recommend dose limits, it recognises that `dose limits for public exposure are rarely limiting in practice' (ICRP, Publication 77, 1997b, paragraph 36). Furthermore, it considers that `...the application of dose limits to waste disposal has intrinsic difficulties' (ICRP, Publication 77, 1997b, paragraph 19) and that control of public exposure through a process of constrained optimisation will `obviate the direct use of the public exposure dose limits in the control of radioactive waste disposal' (ICRP, Publication 77, 1997b, paragraph 48)."

4.2 Dose and risk concepts

(41) The main and primary use of the effective dose in radiological protection for both workers and the general public is (ICRP Publication 103, paragraph 153):

- The prospective dose assessment for planning and optimisation of protection.
- The retrospective dose assessment for demonstrating compliance with dose limits, or for comparing with dose constraints or reference levels.

In practical radiological protection applications, effective dose is used for the demonstration of compliance with protection standards.

(42) A potential exposure is an exposure that is not expected to be delivered with certainty but that may result from an accident at a source or an event or sequence of events of a probabilistic nature, including equipment failures and operating errors. The risk associated with such an event is a function of the probability of an unintended event causing a dose, and the probability of detriment due to that dose. Risk constraints correspond to dose constraints but refer to potential exposures. For potential exposures of workers, the Commission continues to recommend a generic risk constraint of $2\ 10^{-4}$ per year which is similar to the probability of fatal cancer associated with an average occupational annual dose of 5 mSv (ICRP Publication 76). For potential exposures of the public, the Commission continues to recommend a risk constraint of $1\ 10^{-5}$ per year.

4.3 Exposure situations associated with geological disposal

(43) The ICRP system of protection described in its Publication 103 distinguishes three types of radiological situations: planned, existing and emergency situations (ICRP Publication 103, paragraph176).

- **"Planned exposure situations** are everyday situations involving the operation of deliberately introduced sources including decommissioning, disposal of radioactive waste including the post-closure phase and rehabilitation of the previously occupied land. Planned exposure situations may give rise both to exposures that are reasonably anticipated to occur (normal exposures) and to higher exposures that are anticipated to occur with a lower likelihood (potential exposures). These may arise following deviations from normal operating procedures, but are considered at the planning stage."

- **"Emergency exposure situations** are situations that may occur during the operation of a planned situation, or from a malicious act, or from any other unexpected situation, and require urgent action in order to avoid or reduce undesirable consequences."
- **"Existing exposure situations** are exposure situations that already exist when a decision on control has to be taken, including prolonged exposure situations after emergencies."

4.3.1 Exposure situations for waste emplacement activities

(44) In terms of the basic types of exposure situations, waste emplacement activities are subject to the same principles of dose limitations and the requirement to optimise below constraints as those in any nuclear facility. Both worker and public exposures are expected from the transportation, handling and disposal activities and thus, are planned exposures including potential exposures from deviations from the normal operations. The possibility also exists for incidents due to low probability/high consequence initiating events, which could lead to an emergency situation. Operations would be expected to be optimized consistent with the Commission's Recommendations in ICRP Publication 103. The annual dose limits for worker of e.g. 20 mSv in a year is applied with the obligation of optimising protection below dose constraints to be specified by operators. The recommended dose constraint for the public is 0.3 mSv in a year. At the end of the period of direct oversight worker exposures are to be considered in two limited areas of exposure: (1) worker exposure for any indirect monitoring of the facility and its surroundings during the period of indirect oversight, and (2) exposure due to residual radioactivity after decommissioning of the surface facilities.

4.3.2 Exposure situations for the emplaced waste

(45) For the emplaced waste, a typical disposal facility safety assessment would suggest that significant releases are unlikely during the emplacement period and the period of time during which a competently sited, operated and sealed disposal facility is being actively observed and monitored. Therefore, any exposures would be categorised as part of the potential exposure subset of planned exposure. Given the potentially vast time periods involved in the period of no oversight, the possibility of an eventual release of some radioactive substances is inherent in the concept of geological disposal even if the system operates as intended (i.e., without deviations from procedures in operations, construction or accidents). These very long term potential releases of radioactive substances and subsequent exposures are assumed to result from a variety of scenarios. While they may be foreseen and perhaps assigned a probability they are still intrinsically uncertain. Evaluations of these exposures serve the purpose of comparing alternative facility design options and reaching a regulatory judgment regarding the capability of the system to isolate and contain the waste. Such evaluations are not considered to be predictions, nor are they intended to be used for the protection of specific individuals or populations. Such exposures may in fact be projected to occur at such distant times that traditional concepts such as dose and risk have to be used with caution.

(46) Any such releases would be expected to take place well beyond the operational period of the facility so that the immediate causes of any release would be beyond the control of the operator; this suggests that these are uncertain and hence treated as potential exposures. The timing and magnitude of such releases is not predictable except in the broadest sense. Even more, the presence of exposed populations at the point of release as well as their capability to implement protective and/or corrective actions in the far future cannot be assumed certain, should such releases occur.

(47) The process of evaluating the potential exposure from emplaced waste includes the understanding of the potential ways by which the radionuclides could be released from the engineered facility, including the transport through the geosphere to the biosphere and the resultant release into an appropriate environmental compartment that could give rise to exposures to humans, flora or fauna. Depending on the level of knowledge, probabilities may be estimated for these release scenarios. However, at the long timescales considered in geological disposal, evolution of the biosphere and, possibly, the geosphere and the engineered system will increase the uncertainty of these probabilities. Hence the scientific basis for dose and risk assessments at very long times into the future may become questionable and the results of such assessments would then need to be interpreted in a qualitative way.

(48) The expected evolution of a geological disposal facility in the distant future should not require active involvement to mitigate the consequences as this is counter to the principle of avoiding placing an undue burden on future generations. Therefore, the Commission continues to support its recommendations in ICRP Publication 103 that either a dose constraint of 0.3 mSv in a year or an annual risk constraint of $1x10^{-5}$ be used for potential exposures from the emplaced waste. As noted in ICRP Publication 103, it may be useful to disaggregate the probability and potential consequence to reach risk-informed decisions.

(49) In the distant future, in case oversight provisions are no longer operational and the memory of the presence of the disposal facility is lost, it is possible that people will ‘rediscover’ the disposal facility. This may be without compromising its integrity (eg. remote sensing), by observing very small discharges into the biosphere, or it may be by directly breaching the containment, albeit inadvertently, and causing contamination of the environment. Situations of this kind would be treated as an existing exposure situation and be handled as appropriate to the protection guidelines at the time. However, these guidelines are inherently unknowable and thus, while noted, are not relied on for protection decisions today.

4.3.3 Natural disruptive events

(50) The disposal facility and its surrounding environment could be impacted or altered by natural disruptive events, e.g., earthquakes, during the periods of indirect oversight or no oversight. Different scenarios can be envisaged in the future according to the current knowledge. For these events, it may be possible to estimate or bound the probability of occurrence, and the risk of potential consequences should be taken into account in reaching risk-informed waste management decisions.

(51) Natural disruptive events with very low probability compared to the design-basis may occur and may induce significant disturbances on the disposal system or the migration of the radioactive substances. Examples of these types of events include major landform change due to tectonic events, etc. Assessing their probabilities of occurrence may neither be relevant nor feasible. The Commission recommends that the regulatory authority develop a strategy for addressing such events with the involvement of relevant stakeholders. Possible approaches include establishing a probability value for which events with lesser probabilities are excluded from consideration in the risk-assessment process, optimizing site selection to minimize the probability of such events, or assessing specific events through stylized assessments.

(52) Previously the Commission considered all natural events, disruptive or not, within the same framework (Publication 81). Now, the Commission recommends separate consideration of natural disruptive events which are included in the design-basis evolution from those which are not. For the first ones, the Commission recommends application of the dose or risk constraints for planned exposure situation. For the severe natural disruptive events not taken into account in the design-basis evolution, the Commission now recommends application of the reference levels for emergency or existing exposure situations, depending on the severity of the consequences. If the events were to occur, while there is still (direct or indirect) oversight of the disposal facility, the authorities should be in a position to implement adequate protection measures to deal with this situation as emergency or existing exposure situation. If such a disruptive event occurs when oversight of the disposal system has disappeared, there is no certainty about the possibility that an organisation could be aware of the disturbance and therefore, it is not possible to consider with certainty the implementation of protective measures. If the authorities eventually became aware of the disturbance they would treat the situation as an emergency exposure situation or an existing exposure situation depending on the severity of the disturbance.

(53) For emergency exposure situations, the Commission recommends selection of a reference level in the range of 20 mSv to 100 mSv for the first year and development of protection strategies to reduce exposures to as low as reasonably achievable below the reference level taking into account economic and societal factors (Publication 109).

(54) According to Publication 103, long-lasting exposures resulting from natural disruptive events (with or without an emergency phase) should be referred to as an existing exposure situation and the recommended reference levels to be selected for optimizing protection strategies ranges between 1 to 20 mSv per year. In agreement with the Commission's recommendations in Publication 111, a reference level should be selected in the lower part of the band, e.g., in the range of a few mSv per year.

4.3.4 Inadvertent human intrusion

(55) In general, waste is disposed in a geological disposal facility if it needs to be isolated from possible human intrusion (IAEA, 2009). It is necessary to distinguish between deliberate and inadvertent human intrusion into the facility. The first one is not discussed further in this report as it is considered out of the scope of

responsibility of the current generation to protect a deliberate intruder, i.e. a person who is aware of the nature of the facility. The design and siting of the facility will have to include features to reduce the possibility of inadvertent human intrusion.

(56) A release resulting from inadvertent human intrusion, such as drilling into the facility, could migrate through the geosphere and biosphere resulting in exposures that are indirectly related or incidental to the intrusion event. It is also possible that inadvertent human intrusion could bring waste material to the surface and hence lead to direct exposure of the intruder and nearby populations. This introduces the possibility of elevated exposures and significant doses which is an inescapable consequence of the decision to isolate and contain waste rather than diluting or dispersing it.

(57) Protection from exposures associated with human intrusion is best accomplished by efforts to reduce the assumed possibility of such events. These may include siting a disposal facility at great distance from the surface, avoiding assumed valuable resources, incorporating robust design features which make intrusion more difficult, or employing direct oversight (such as restricting access or monitoring for releases) and indirect passive oversight (such as archived record and site markers). While the actual probability of human intrusion at a specific site is largely unknowable as it is based on future human actions, it is assumed that the probability of intrusion during the direct and indirect oversight periods is effectively zero.

(58) For longer time periods, in case oversight has disappeared, the occurrence of human intrusion cannot be totally ruled out. Therefore, the consequences of one or more plausible stylised intrusion scenarios should be considered by the decision-maker to evaluate the resilience of the disposal facility to potential inadvertent intrusion. Any estimates of the magnitude of intrusion risks are by necessity dependent on assumptions that are made about future human behavior. Since no scientific basis exists for predicting the nature or probability of future human actions, the Commission continues to consider not appropriate to include the probabilities of such events in a quantitative performance assessment that is to be compared with dose or risk constraints (Publication 81). If recognized at the time an intrusion occurs, it would be treated as an emergency exposure situation or an existing exposure situation depending on the severity of the related disturbance.

(59) The Commission wishes to emphasise that the dose criteria specified in Publication 81 for human intrusion only apply to near surface disposal. In case of geological disposal, intrusion means that many of the barriers which were considered in the optimization of protection for the disposal facility have been by-passed. Since a future society may be unaware of the radiation risk associated with such events, any protective actions required should be considered during the development of the disposal system. Therefore the dose or risk constraints recommended by the Commission for the application of the optimization of protection in geological disposal do not apply to inadvertent human intrusion.

4.3.5 Summary of relevant exposure situation according oversight

(60) The application of the three exposure situations and of dose limits, dose

constraints and reference levels as defined in ICRP Publication 103 during these timeframes is indicated in Table 1.

RADIOLOGICAL EXPOSURE SITUATIONS AS FUNCTION OF DISPOSAL FACILITY EVOLUTION AND PRESENCE AND TYPE OF OVERSIGHT			
Disposal facility Status	**Type of Oversight**		
	Direct Oversight	**Indirect Oversight**	**No oversight**
Design-basis[1] evolution	Planned Exposure Situation[2]	Planned Exposure Situation[2]	Planned Exposure Situation[2,3]
Non-design basis evolution involving significant exposures to people and the environment	Emergency Exposure Situation at the time of exposure, followed by an Existing Exposure Situation[4]	Emergency Exposure Situation at the time of exposure, followed by an Existing Exposure Situation[4]	Emergency and/or Existing Exposure Situation
Inadvertent Human Intrusion	not relevant	not relevant	Emergency and/or Existing Exposure Situation

[1] The design basis is the envelope of both expected and less likely (potential) events that are used in planning the facility.

[2] At design: 20 mSv/a dose limit to worker and dose constraint to be specified by operators; 1 mSv/a dose limit and 0.3 mSv/a dose constraint for the public; in the case of less likely events within the design basis a risk constraint of 1 10^{-5} per year for the public is suggested.

[3] No worker dose is foreseen during the period of no oversight

[4] For an emergency exposure situation a reference level between 20 and 100 mSv per year is recommended; for an exisiting exposure situation a reference level should be selected in the lower part of the band between 1 and 20 mSv per year, eg., in the range of a few mSv per year.

4.4 Optimisation and Best Available Techniques

(61) The principle of optimisation is defined by the Commission (ICRP Publications 101 and 103) 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. The general recommendations for the optimisation process are described in ICRP Publication 101, part 2.

(62) The ICRP principle of optimisation of radiological protection when applied to the development and implementation of a geological disposal facility has to be understood in the broadest sense of an iterative, systematic and transparent evaluation of options for enhancing the protective capabilities of the system and for reducing impacts (radiological and others).

(63) 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 isolating the waste from man, the environment and the biosphere and by containing the radioactive and

other toxic substances in the waste to the largest extent possible. Optimisation of protection has to deal with the protection of workers and the public during the time of operation, as well as with the protection of future generations including possible periods with no oversight, and safety has to be ensured by a passively functioning disposal system.

(64) The stepwise decisional process for geological disposal facility development and implementation constitutes the framework for the optimisation process. As a central component, optimisation has to cover all elements of the disposal system in an integrative approach, i.e. site (incl. host formation), facility design, the application of Best Available Techniques (BAT), waste package design, waste characteristics as well as all relevant time periods.

(65) Optimisation of protection is a multi-facet endeavour, involving the disposal facility developer, safety and environmental protection authorities, local communities and other stakeholders and multiple decisions have to be taken. Therefore, it is not possible to define a priori the path for a sound optimisation process for a geological disposal facility, or the acceptance or success criteria for the end result of an optimisation process.

(66) Socio-economical factors (including e.g. policy decisions and societal acceptance issues) can constraint the optimisation process to various extents, e.g. by limiting the available options (e.g. siting) and/or by defining additional conditions (e.g. retrievability). It is important that these constraints are identified in a manner transparent to all involved stakeholders and that their safety implications are generally and broadly understood. These factors must not force the optimisation process to accept options that are questionable from a protection point of view.

(67) Although optimisation is a continuous effort, milestones will have to be defined in the stepwise process, where all involved stakeholders can judge the result of the optimisation process and indicate ways to improve various elements of the system.

(68) The process of optimisation will be considerably different for the pre-operational, operational and post-operational phases. During the operational phase, the general recommendations for any large nuclear facility apply. Experience gained during the operational phase can be factored into immediate or near term improvements, reducing the exposure to both workers and the public from the emplacement work.

(69) Nearly all aspects of optimisation for the post-operational phase must occur prior to waste emplacement, largely in the siting and design phase, with the plans to close the facility being part of the design phase. Some further optimisation of the protection that will be provided during the post-operational phase is still possible during the operational phase, for example as new materials or techniques may become available. Experience gained during the closure of parts of the facility, e.g. sealing of disposal rooms, can lead to improvements of the plans of the disposal facility closure.

(70) During the post-operational phase, there is no active operation of the disposal facility. The waste is emplaced and the protection of humans and the environment is mainly based on the passive isolation and containment capabilities of the disposal

system. Hence decisions on optimisation in the post-operational phase can only relate to the time and method of oversight of the closed disposal system. During this phase optimisation of protection can best be achieved by maintaining oversight.

(71) Geological disposal facilities are sited, designed and implemented to provide for robust long-time isolation and containment, resulting in potential impacts on humans and the environment only in the very far future. Consequently, as explained earlier, the assessment of post-closure radiological impacts through the estimation of effective dose or risk to a reference person, given the increasing uncertainties with time and the cautious assumptions to be made, can only provide an indication or illustration of the robustness of the system, rather than predictions of future radiological consequences. As previously discussed, there comes a time in the distant future beyond which any such calculated dose or risk values must be considered for the sake of comparison of options rather than as absolute values.

(72) 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 safety functions of isolation and containment in a robust manner. The assessment and judgment of the quality of system components essentially includes elements of BAT as well as the concepts of good practice and sound engineering and managerial principles. These elements complement and support radiological optimisation when potential impacts in the far future have to be dealt with.

(73) The judgment of the quality of the system design developed or implemented has to be made, and critically reviewed 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.

(74) When dealing with safety in the more distant future, optimisation can be complemented and supported by applying the concept of BAT on the various levels of the disposal system, through:

- the methodologies for identifying and selecting (a) host rock(s), zones and sites, and the methodological and scientific program of host rock and site characterization in order to assess its containment and isolation capacities now and in the distant future;
- the development of the system design, including the choices of materials and technologies, and the way they will contribute, individually and together, to the main aim of isolation and containment, taking due account of the characteristics of the host rock;
- the integration of waste, site and design characteristics within one disposal system and the iterative assessment of the isolation and containment capacities of the system as a whole;
- the use of sound managerial and engineering methods and practices during system construction, operation and closure, within an integrated management system.

(75) Optimisation on the basis of radiological criteria (effective dose and risk) is an important part of the optimisation of the design and implementation process of the disposal facility at specific “windows” and for specific aspects of the disposal facility, e.g. when operational safety is assessed during the design development steps and during preparation and implementation of operational procedures and activities.

(76) The way the various elements of a disposal system can be optimized in an integrative manner during system development varies to a large extent. First of all stepwise optimisation decisions have to be taken mostly in a chronological order: e.g. the decisions on the choice of a host rock and on one or a limited number of sites are often prior to decisions on a detailed design. For the selection of a host rock and a site, a balance has to be struck between technical criteria related to the safety of a disposal system (long-term stability, barrier for radionuclide migration, absence or presence of natural resources in the vicinity, …) and the requirement of local or supra-local societal acceptance. Favourable host rocks and sites can in a first step be identified on the basis of broadly defined “required qualities”, taking due account of the isolation and containment function(s) of the natural barriers and the natural environment in the disposal system.

(77) If several suitable host rocks or sites can be identified and evaluated the decision in favour of one specific host rock or site will always be a multi-factor decision, based on both qualitative and quantitative judgments. Radiological criteria (e.g. calculated effective dose) are often of limited value for this multi-factor decision, due to (1) the increasing uncertainties for longer assessment timescales, and (2) the observation that often calculated radiological impacts are so low that they do not constitute a discriminating factor for the choice of a host rock or site.

(78) The assessment of the robustness of the disposal facility can contribute to system optimisation, because it provides insight, quantitative or qualitative, in the performance of the disposal facility and its components, in the relative contributions of the various components to the overall system. So, the value of such an assessment for the optimisation process is mainly through the insights it provides on the relative contributions of the various components to the overall system objective of isolation and containment, and how these contributions can be affected by disturbing events and processes or by remaining uncertainties. The indicative nature of calculated effective dose and risk in the very far future reduces their usefulness for the optimisation process.

5. „Endpoint considerations“

5.1 The Representative Person

(79) As general guidance, the Commission considers that its recommendations on the estimation of exposures in Publication 101, part 1, apply. The Commission therefore continues to recommend that for planned exposure situations exposures should in general be assessed on the basis of the annual dose to the representative person.

(80) During the operational phase, management of exposures to workers and the

public would be the same as for any other large nuclear facility. During the post-operational phase, due to the long time-scales under consideration, the habits and characteristics of the representative person, as well as those of the environment in which it is located, can only be based on a number of assumptions. In that case, any such representative person has to be hypothetical and stylized. The habits and characteristics assumed for the individual in a distant 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 different representative persons, may be considered for the long term and have different probabilities of occurrence, although establishing discreet probabilities may be problematic. Thus, the scenario leading to the highest dose may not be linked to the highest risk. It is therefore important for the decision-maker to have a clear presentation of the different scenarios and their associated probabilities of occurrence or at least with an appreciation of their corresponding probabilities.

(81) As stated in ICRP Publication 101, part 1, 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 hypothetical representative person is located at the time and place of the maximum concentration of radionuclides in the biosphere. This is an assumption since the environment may have evolved such that humans are no longer inhabiting these areas in the far future.

(82) A representative person cannot be defined independently of the assumed biosphere. Major changes may occur in the biosphere in the long-term due to the action of natural forces in a similar manner to those occurring in the past. Human actions may also affect the biosphere, but one can only speculate about human behaviour in the long-term. In the definition of the scenarios, consideration of biosphere changes should be limited to those due to natural forces. A representative person and biosphere should be defined using either a site specific approach based on site or region specific information or a stylized approach based on more general habits and conditions; the use of stylized approaches will become more important for longer time-scales.

(83) In the long term, if radionuclides are present in the environment, exposures of the representative person are expected to occur during a whole lifetime. The Commission recommends in its Publication 101, part 1, to use three age categories for estimating annual dose to the representative person, for comparison with annual dose or risk criteria. (Note that 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). These categories are 0-5 years (infant), 6-15 years (child), and 16-70 years (adult). Decisions can also be made by considering doses or risks on a lifetime exposure instead on a per annum scale. For the comparison of doses to individuals of current and future generations, however, it may be necessary to calculate doses for different age groups for future exposures from the radioactive waste site or vice versa to calculate doses for a representative person of the current generation on the basis of lifetime exposure.

5.2 Protection of the environment

(84) Illustration that the environment is protected against harmful effects of releases from facilities is an increasing requirement in national legislation and in relation to many human activities including the management of long-lived waste. ICRP has responded to this need as well as to a number of other requirements of ethical nature (as laid out in its Publication 91) by directly and specifically addressing environmental protection in ICRP Publication 103 and by offering a methodology to address this issue, as outlined in ICRP Publication 108.

(85) The ICRP approach considers the health of the environment (not the presence of contamination or other factors that may affect the environment as a resource), with 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 Publication 103 para 30). The full evaluation of environmental impact would normally be assessed through the Environmental Impact Assessment process and in the Environmental Impact Statement, where effects will be considered within a broader context including such factors as inter alia, visual impact, chemotoxic impact, noise, land use and amenities.

(86) The default target for protection and protective actions could be the set of Reference Animals and Plants that have been described by ICRP and for which the relevant data sets have been derived (Publication 108). The use of Reference Animals and Plants offers on one hand a challenge for waste management which is at least similar to the challenges of demonstrating compliance with dose/risk standards; but, on the other hand, also 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. Consideration of environmental protection, where appropriate, would thus broaden the basis for risk-informed decision making and addressed issues that may have differing levels of importance for different stakeholders.

(87) Over the long time frames that are considered in waste disposal, the biosphere is likely to change, and even change substantially. Such changes entail biosphere evolution with time that is either natural, or enhanced or perturbed through human action. Contributing factors may be, e.g., climate change including glaciations cycles, and land uplift or depression. Understanding different biospheres today and assessing impacts in such biospheres based on an approach involving Reference Animals and Plants, may guide our understanding of future biosphere changes also for the purpose of environmental protection.

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Annex 1: The ICRP system of protection, focusing on aspects relevant to the geological disposal of long-lived solid radioactive waste

The purpose of this annex is to summarize the key recommendations of ICRP relevant to waste disposal.

In its Publication 103, the ICRP Recommendations evolve from the previous process-based protection approach using practices and interventions by moving to an approach based on the exposure situation. They recognise planned, emergency, and existing exposure situations, and apply the fundamental principles of justification and optimisation of protection to all of these situations. They maintain the Commission's current individual dose limits for effective dose and equivalent dose from all regulated sources in planned exposure situations. They reinforce the principle of optimisation of protection, which should be applicable in a similar way to all exposure situations, subject to the following restrictions on individual doses and risks; dose and risk constraints for planned exposure situations, and reference levels for emergency and existing exposure situations. The Recommendations also include an approach for developing a framework to demonstrate radiological protection of the environment.

I. Principles of Protection

The three fundamental principles of protection are

- ***Justification***: Any decision that alters the exposure situation should do more good than harm. This means that, by introducing a new source, by reducing existing exposure, or by reducing the risk of potential exposure, one should achieve sufficient individual or societal benefit to offset the detriment it causes.

  Waste management and disposal operations are an integral part of the practice generating the waste. It is wrong to regard them as a free standing practice that needs its own justification. The waste management and disposal operations should therefore be included in the assessment of the justification of the practice generating the waste (ICRP 77 §34). This assessment should include considerations of different options for waste management and disposal including the justification of these options. If the national waste disposal policy has changed and the practice is continuing, it may be necessary to reassess the justification of the practice. If the practice has ceased, the protection strategy, rather than the practice, has to be considered for justification.

- ***Optimisation of protection***: 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. This means that the level of protection should be the best under the prevailing circumstances, maximising the margin of benefit over harm. In order to avoid severely inequitable outcomes of this optimisation procedure, there should be restrictions on the doses or risks to individuals from a particular source.
- ***Application of dose limits***: The total dose to any individual from

regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits recommended by the Commission. Regulatory dose limits are determined by the regulatory authority, taking account of international recommendations, and apply to workers and to members of the public in planned exposure situations.

The role of optimisation

When optimising protection strategies, it is necessary to consider all aspects and protective measures to reduce residual dose, questioning whether 'the best has been done in the prevailing circumstances, and if all that is reasonable has been done to reduce doses' (ICRP Publication 103, Para. 217). This approach focuses efforts on optimising protection in order that individual exposures, from all pathways, resulting from the operation of a waste disposal facility (i.e. residual doses) are judged to be acceptable in the context of the circumstances being planned for and the expected resources required/allocated for protection. This approach implies the simultaneous optimisation of all protective measures that are included in the protection strategy, implemented if necessary in a stepwise fashion to address prevailing circumstances appropriately.

All aspects of optimisation cannot be codified; rather, there should be a commitment by all parties to the optimisation process. Where optimisation becomes a matter for the regulatory authority, the focus should *not* be on specific outcomes for a particular situation, but rather on processes, procedures, and judgements. An open dialogue should be established between the authority and the operating management, and the success of the optimisation process will depend strongly on the quality of this dialogue.

Societal values usually influence the final decision on the level of radiological protection. Therefore, while this report should be seen as providing decision-aiding recommendations mainly based on scientific considerations on radiological protection, the Commission's advice will be expected to serve as an input to a final (usually wider) decision-making process, which may include other societal concerns and ethical aspects, as well as considerations of transparency (ICRP Publication 101). This decision-making process may often include the participation of relevant stakeholders rather than radiological protection specialists alone.

II. Types of exposures and of exposure situations

The Commission distinguishes between three categories of exposure: occupational, public, and medical exposures of patients.

The Commission intends its Recommendations to be applied to all sources and to individuals exposed to in the following three types of exposure situations which address all conceivable circumstances (ICRP Publication 103, para.176).

- **Planned exposure situations** are situations involving the deliberate introduction and operation of sources; including decommissioning, disposal of radioactive waste and rehabilitation of the previously occupied land. Planned exposure situations may give rise both to exposures that are anticipated to occur (normal exposures) and to exposures that are not anticipated to occur (potential exposures).

- **Emergency exposure situations** are situations that may occur during the operation of a planned situation, or from a malicious act, or from any other unexpected situation, and require urgent action in order to avoid or reduce undesirable consequences.
- **Existing exposure situations** are exposure situations that already exist when a decision on control has to be taken, including prolonged exposure situations after emergencies.

It follows that what the Commission has previously called 'practices' could be the origin of planned, emergency, and existing exposure situations. The principles of protection for planned situations also apply to occupational exposure in connection with existing and emergency exposure situations.

III. Dose concepts (effective dose, collective dose)

The main and primary uses of **effective dose** in radiological protection for both occupational workers and the general public are (ICRP Publication 103, para. 153):

- prospective dose assessment for planning and optimisation of protection; and
- retrospective dose assessment for demonstrating compliance with dose limits, or for comparing with dose constraints or reference levels.

In practical radiological protection applications, effective dose is used for managing the risks of stochastic effects in workers and the public.

The overall exposure, which is projected to occur as a result of the emergency exposure situation, should no protective actions be employed, is called the *projected dose*. The dose that would result when a protection strategy is implemented is called the *residual dose*. In addition, each protective measure will avert a certain amount of exposure. This is referred to as *averted dose*.

ICRP Publication 103, para. 159: For the purpose of optimisation of radiological protection, predominantly in the context of occupational exposure, the Commission has introduced **collective dose** quantities (ICRP Publication 26). These quantities take account of the exposure of all individuals in a group over a given time period or during a given operation executed by this group in designated areas. Collective effective dose is not intended as a tool for epidemiological studies, and it is inappropriate to use it in risk projections.

IV. Dose limits, constraints and reference levels

(B 174) In practice, limits, constraints, reference levels, and action levels are defined in terms of dose quantities in order to restrict the risks from exposure for both occupational workers and the public. Since neither quantity can be directly measured, they are assessed using other measurable quantities, models and computations. Depending on the situation considered (occupational or public exposure), different procedures are applied.

Dose limit

The value of the effective dose or the equivalent dose to individuals from planned exposure situations that shall not be exceeded. Numerical values are given in Tab. 8 (ICRP Publication 103).

Dose constraint
A prospective and source-related restriction on the individual dose from a source, which provides a basic level of protection for the most highly exposed individuals from a source, and serves as an upper bound on the dose in optimisation of protection for that source. For occupational exposures, the dose constraint is a value of individual dose used to limit the range of options considered in the process of optimisation. For public exposure, the dose constraint is an upper bound on the annual doses that members of the public should receive from the planned operation of any controlled source. Numerical values are given in Tab. 8 (ICRP Publication 103).

Reference level
In emergency or existing exposure situations, the reference level represents the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimisation of protection should be implemented. The chosen value for a reference level will depend upon the prevailing circumstances of the exposure under consideration. Numerical values are given in Tab. 8 (ICRP Publication 103).

Derived consideration reference level
For the purpose of environmental protection, ICRP has in Publication 108 identified Derived Consideration Reference Levels (DCRLs). These are 'bands' of environmental dose (expressed as absorbed dose) rates, spanning one order of magnitude, for the different Reference Animals and Plants, that "can be considered a band of dose rates within which there is likely to be some chance of deleterious effects occurring to individuals of that type of Reference Animal or Plant....that, when considered with other relevant information, can be used as a point of reference to optimise the level of effort expended on environmental protection (Publication 108, para. 195).

Potential exposure is an exposure that is not expected to be delivered with certainty but that may result from an accident at a source or an event or sequence of events of a probabilistic nature, including equipment failures and operating errors.

Risk constraint
A prospective and source-related restriction on the individual risk (in the sense of probability of detriment due to a potential exposure) from a source, which provides a basic level of protection for the individuals most at risk from a source and serves as an upper bound on the individual risk in optimisation of protection for that source. This risk is a function of the probability of an unintended event causing a dose, and the probability of detriment due to that dose. Risk constraints correspond to dose constraints but refer to potential exposures.

ICRP Publication 103, para. 268: Risk constraints, like dose constraints, are source-related and in principle should equate to a similar health risk to that implied by the corresponding dose constraints for the same source. However, there can be large uncertainties in estimations of the probability of an unsafe situation and the resulting dose. Thus, it will often be sufficient to use a generic value for a risk constraint. In the case of workers, this could be based on generalisations about normal occupational exposures, rather than on a more specific study of the particular operation. For potential exposures of **workers**, the Commission continues to recommend a generic risk constraint of **2 10^{-4} per year** which is similar to the probability of fatal cancer associated with an average occupational annual dose of 5 mSv (ICRP, Publication 76). For potential exposures of the **public**, the Commission continues to recommend a risk constraint of **1 10^{-5} per year**.

V. Protection of the environment.

The Commission acknowledges that, in contrast to human radiological protection, the objectives of environmental protection are both complex and difficult to articulate. The Commission does however subscribe to the global needs and efforts required to maintain biological diversity, to ensure the conservation of species, and to protect the health and status of natural habitats, communities, and ecosystems. It also recognises that these objectives may be met in different ways, that ionising may be only a minor consideration – depending on the environmental exposure situation – and that a sense of proportion is necessary in trying to achieve them (ICRP Publication 103, para. 361).

The Commission therefore believes that the development of a clearer framework is required in order to assess the relationships between exposure and dose, and between dose and effect, and the consequences of such effects, for non-human species, on a common scientific basis. This issue was first discussed in ICRP Publication 91, and it was concluded that it was necessary to draw upon the lessons learned from the development of the systematic framework for the protection of human beings. This framework is based on an enormous range of knowledge that the Commission attempts to convert into pragmatic advice that will be of value in managing different exposure situations, bearing in mind the wide range of errors, uncertainties, and knowledge gaps of the various databases (ICRP Publication 103, para. 364).

The Commission does not therefore propose to set any form of ‘dose limits’ with respect to environmental protection. However, by setting out data for some Reference Animals and Plants, in a transparently derived way, and upon which further action may be considered, the Commission offers practical advice as laid out in Publication 108. The Commission will continue to develop this framework to gather and interpret data in order to provide more comprehensive advice in the future, particularly with regard to those aspects or features of different environments that are likely to be of concern under different exposure situations (ICRP Publication 103, para. 370)

VI. Stakeholder involvement

Since the mid 90s, the involvement of stakeholders in decision making related to protection issues has been recognised as a key process notably for favouring the understanding of the protection measures, improving the protection, adapting the measures to the local context and ensuring the sustainability of the protection. ICRP Publication 82 (1999) is the first ICRP Publication mentioning explicitly stakeholder involvement: “Many situations of prolonged exposure are integrated into the human habitat and the Commission anticipates that the decision-making process will include the participation of relevant stakeholders, rather than radiological protection specialists alone.” (para. 4).

Furthermore, in ICRP Publication 91 (2003) stakeholder involvement is introduced as part of the “principles” for protecting the environment: “The principle of informed consent, which emphasises the need for communication and public involvement, starting at the planning stage and well before decisions are taken from which there is no return. Such transparency of decision making should enable analysis and understanding of all stakeholder’s arguments… » (Current environmental management principles, para. 47).

In ICRP Publication 101 Part 1 (2006), dealing with Assessing Dose of the Representative Person for the Purpose of Protection of the Public, there is a first elicitation of the advantages of engaging stakeholders: “In the case of defining characteristics of the representative persons, stakeholder involvement can play an important role… In particular, stakeholders can be helpful in determining the reasonableness, sustainability, and homogeneity of habit data. Collaboration with stakeholders can significantly improve the quality, understanding and acceptability of characteristics of the representative person, and also strengthen support for the process and the results.” (Value of stakeholder input in characterising the representative person, § 102).

It is then reinforced in ICRP Publication 101 Part 2 (2006) as well as in ICRP Publication 103 (2008) for the Optimisation of Radiological Protection: “The involvement of stakeholders is a proven means to achieve incorporation of values into the decision-making process, improvement of the substantive quality of decisions, resolution of conflicts among competing interests, building of shared understanding with both workers and the public, and building trust in institutions. Furthermore, involving all concerned parties reinforces the safety culture and introduce the necessary flexibility in the management of the radiological risk that is needed to achieve more effective and sustainable decisions.” (The optimisation process, ICRP Publication 101 Part 2, para. 39).

More recently, stakeholder engagement processes were considered as key components of the development of strategies in case of preparedness of emergency situations and management of existing situations. (ICRP Publication 109 related to the Application of the Commission’s Recommendations for the Protection of People in Emergency Exposure Situations and ICRP Publication 111 related to the Application of the Commission’s Recommendations to the Protection of People Living in Long Term Contaminated Areas After a Nuclear Accident or a Radiological Emergency).

These considerations fully apply to radioactive waste management. The Commission recognises that the nature and extent of stakeholder involvement may vary between countries, but suggests that engagement with stakeholders is an important component to the justification and optimisation of protection strategies in waste disposal projects. During planning, it is essential that the plan is discussed, to the extent practicable, with relevant stakeholders, including other authorities and the public. Otherwise, it will be difficult to implement the plan effectively during operation. The overall protection strategy and its constituent individual protective measures should have been worked through with all those potentially exposed or affected.

In addition, because of the long time scale at stake, it is also necessary to consider the role of stakeholders to deal with intergenerational transmission of knowledge and memory of installations and protection strategies.

Annex 2 ICRP use of "potential exposure"

ICRP has frequently used the term „potential exposure" in its publications:

> *"…..The 1955 Conference on the Peaceful Uses of Atomic Energy had aroused great interest in the development of atomic power plants throughout the world. In time this would greatly increase the number of persons occupationally exposed and would also bring about actual or* ***potential exposure*** *of other persons and the population as a whole." (ICRP Publications 1, 3, 4).*

Further uses of the term „potential exposure" can be found in ICRP recommendations related to various fields of radiological protection (Publ. 10, 36, 37, 40, 42, 43, 54, 57).

The first comprehensive discussion of the nature and application of the term „potential exposure" is given in ICRP Publ. 60 and 64 (Protection from potential exposure):

> *"(2) exposure which might result from the introduction of a practice is also divided into two broad categories: normal exposure and* ***potential exposure****. Normal exposure is that exposure which can reasonably be expected to occur, i.e., the exposure is predicted to occur with a probability of one or near one, independent of the time when the exposure occurs. It includes both exposure from operations conducted as planned as well as unintended high probability, low consequence events. These events are nearly certain to occur during operations but result in doses that are within prescribed limits.* ***Potential exposure*** *is exposure that, while not certain to occur, can be anticipated as a result of introducing or modifying a practice and to which a probability of occurrence can be assigned. Such exposure involves consideration of risk which falls outside the general boundaries considered for normal exposure. The occurrence of potential events and the chances that such events will result in a dose to an individual or group of individuals, when combined with the probability of effects from the expected resulting dose, can be presented as an a priori probability of harm. The initial consideration of potential exposures, therefore, should form part of the system of protection applied to practices, but it should be recognised that the exposures, if they occur, may lead to intervention (ICRP, 1991)."*
>
> *(4) Potential exposure situations may arise from the introduction of most, if not all, practices and involve a large variety of potential consequences. ….. There are also potential exposure situations, such as those associated with radioactive waste disposal, which can arise in the far distant future where consequences become much more difficult to predict. Although safety for this wide spectrum of situations should be governed by coherent and consistent principles, the level of effort required to implement the principles and the formulation of acceptance criteria will differ substantially depending on the complexity of the practice, sophistication of the engineering safety systems and the possible consequences.*
>
> *(5) In practical application, a system of protection against potential exposure must apply fundamental safety principles developed for complex technical systems…... The report is intended to show how the fundamental safety principles can be applied to all potential exposure situations….. Although the methods of application of those principles may be less complex for a less complex source of , a conscientious application of the safety principles to the design and operation of*

sources appears appropriate to reduce the risk of accidental exposure in many industrial and medical practices.

(11) In order to maintain a strict coherence in the treatment of actual and potential exposures, it is necessary to extend the concept of detriment to include the probability of occurrence of the situation giving rise to the detriment…. emphasis has to be placed on one part of detriment - the probability of an attributable death. However, nominal probability coefficients for stochastic effects that include non-fatal cancer and severe hereditary effects can be used in considering detriment to individuals from potential exposure. It must also be recognised that the uncertainties in estimating the probability of occurrence will usually be much greater than the uncertainties in estimating the probability of the consequences, should the dose occur.

(33) The system of radiological protection recommended by the Commission for proposed and continuing practices is based on the following general principles.

(b) In relation to any particular source within a practice, the magnitude of individual doses, the number of people exposed and the likelihood of incurring exposures where these are not certain to be received should all be kept as low as reasonably achievable, economic and social factors being taken into account. This procedure should be constrained by restrictions on the doses to individuals (dose constraints), ***or the risks to individuals in the case of potential exposures (risk constraints)****, so as to limit the inequity likely to result from the inherent economic and social judgments. (The optimisation of protection)*

(61) Limits are used in safety to control the risk to individuals from all stipulated sources of exposure. However, in order to establish requirements to constrain exposure to individuals from a particular source, the Commission has recommended the use of constraints in the process of optimisation, which are source related and should be established in a manner such that the sum of the risks from all relevant sources does not exceed the individual limit. ***For the treatment of potential exposure, the Commission recommends that limits of risk be of the same order of magnitude as the health risk implied by the dose limits for normal exposures. However, the dose limits themselves are not applicable to potential exposure situations.***

Table 1. Range of probabilities in a year from which constraint may be selected

Sequence of events leading to doses treated as part of normal exposures	10^{-1} to 10^{-2}
Sequence of events leading to stochastic effects only but above dose limits	10^{-2} to 10^{-5}
Sequence of events leading to doses where some radiation effects are deterministic	10^{-5} to 10^{-6}
Sequence of events leading to doses where death is likely to result	$< 10^{-6}$

The guidance provided in Publication 64 has been used and further developed in ICRP Publications 73, 77, 81, 82, 92, 94 and 101.

Publication 103 confirms the basic principles by the following statements:

Para. 176: Planned exposure situations are situations involving the deliberate introduction and operation of sources. Planned exposure situations may give rise *both to exposures that are anticipated to occur (normal exposures) and to exposures that are not anticipated to occur (**potential exposures**).*

*Para. 205: The Commission recommends that, when activities involving an increased or decreased level of exposure, **or a risk of potential exposure**, are being considered, the expected change in detriment should be explicitly included in the decision-making process.*

*Para 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**…*

*Para 229: In Table 4 the different types of dose restrictions used in the Commission's system of protection (limits, constraints, reference levels) are shown in relation to type of exposure situation and category of exposure. In planned exposure situations, there are also **risk constraints in order to take account of potential exposures**.*

*Para 254: All categories of exposure can occur in planned exposure situations, i.e., occupational exposure, public exposure, and medical exposure of patients….. The design and development of planned situations should have proper regard **for potential exposures** that may result from deviations from normal operating conditions. Due attention should be paid to the assessment of **potential exposures** and to the related issue of the safety and security of sources.*

Chapter 6.1.3 provides further details.

Para 265 states: "Events in which the potential exposures could occur far in the future, and the doses be delivered over long time periods, e.g., in the case of solid waste disposal in deep repositories: Considerable uncertainties surround exposures taking place in the far future. Thus dose estimates should not be regarded as measures of health detriment beyond times of around several hundreds of years into the future. Rather, they represent indicators of the protection afforded by the disposal system. The Commission has given specific guidance for the disposal of long-lived solid radioactive waste in Publication 81 (ICRP, 1998b). This guidance remains valid."

Para 267: The principles of constructing and analysing scenarios are well known and are often used in engineering. Their application was discussed in Publication 76 (ICRP, 1997b). Decisions on the acceptability of potential exposures should take account of both the probability of occurrence of the exposure and its magnitude. In some circumstances, decisions can be made by separate consideration of these two factors. In other circumstances, it is useful to consider the individual probability of -related death, rather than the effective dose (ICRP, 1997b). For this purpose, the probability is defined as the product of the probability of incurring the dose in a year and the lifetime probability of -related death from the dose conditional on the dose being incurred. The resulting probability can then be compared with a risk constraint. If the probability is lower than the risk constraint, it may be tolerated. Both of these approaches are discussed in the Commission's Recommendations for the disposal of long-lived solid radioactive waste in Publication 81 (ICRP, 1998b).

Para 268: Risk constraints, like dose constraints, are source-related and in principle should equate to a similar health risk to that implied by the corresponding dose constraints for the same source. However, there can be large uncertainties in estimations of the probability of an unsafe situation and the *resulting dose. Thus, it will often be sufficient to use a generic value for a risk constraint. In the case of workers, this could be based on generalisations about normal occupational exposures, rather than on a more specific study of the particular operation. Where the Commission's system of dose limitation has been applied and protection is optimised, annual occupational effective doses to an average individual may be as high as about 5 mSv in certain selected types of operation (UNSCEAR, 2000). For potential exposures of* ***workers****, the Commission therefore continues to recommend a generic* ***risk constraint of*** $2\ 10^{-4}$ *per year which is similar to the probability of fatal cancer associated with an average occupational annual dose of 5 mSv (ICRP, 1997b). For potential exposures of the* ***public****, the Commission continues to recommend a* ***risk constraint of*** $1\ 10^{-5}$ ***per year****.*

Both dose and risk constraints should be applied in planned exposure situations. For the specific situation of waste disposal dose constraints can be used for comparison of options for normal releases, referred as “desing-basis evolution” of the depository facility. Events with lower probabilities than the desing-basis evolution should be treated as potential exposures and would require the application of relevant risk constraints. Risk constraints will be applied either in an aggregated or a disaggregated way.

Annex 3 Technical and management principles and requirements

Ref.: ICRP 101 section 6.6.4, §315, 316 ff

The general implementation of the Commission's recommendations on the disposal of radioactive waste requires that organizational and managerial structures and processes are put into place, and that technical principles are applied. Organizational structures and processes can largely differ from country to country, but should be based on the principles laid down by the IAEA in its Fundamental Safety Principles.

The Commission recommends that management principles and requirements should be applied to the disposal system development and implementation process to enhance the confidence that the protection of humans and the environment will be ensured for as long as needed.

Management systems play an important role "to improve the safety performance of the organization through the planning, control and supervision of safety related activities in normal, transient and emergency situations" and "to foster and support strong safety culture through the development and reinforcement of good attitudes and behaviour in individuals and teams so as to allow them to carry out their tasks safely" (IAEA GS-R-3).

The general requirements for establishing, implementing, assessing and continually improving a management system have been formulated by IAEA, and specific recommendations for the management system for the disposal of radioactive waste in IAEA Safety Standards publication GS-G-3.4.

A management system designed to fulfill the international IAEA requirements integrates safety, health, environmental, security, quality and economic elements, with safety being the fundamental principle upon which the management system is based. "*The main aim of the management system shall be to achieve and enhance safety by:*

- *bringing together in a coherent manner all the requirements for managing the organization;*
- *describing the planned and systematic actions necessary to provide adequate confidence that all these requirements are satisfied;*
- *ensuring that health, environmental, security, quality and economical requirements are not considered separately from safety requirements, to help preclude their possible negative impact on safety." (IAEA GSG-3.4)*

Maintaining and further developing knowledge, competences and skills for the disposal of radioactive waste, as an essential element to ensure high levels of safety, should be based on a combination of scientific research and technological development, insights gained from successive safety cases, learning through operational experience and technical cooperation between all actors. Independent reviews, transparency and accessibility of information, and openness to stakeholder participation are also important contributors for ensuring high levels of safety.

A key technical principle for developing disposal systems and assessing their safety is the concept of defence in depth which provides for successive passive safety measures, enhancing the confidence that the disposal system is robust and has an adequate margin of safety. The defence in depth concept as applied to disposal systems imposes that safety is provided by means of the various components of the system contributing to fulfilling the main safety functions in different ways over different timescales. The performance of the various components contributing to fulfilling the main safety functions has to be achieved by diverse physical and chemical processes, such that the overall performance of the system will not be unduly dependent on a single component or function. The main safety objective of the siting (a.o. selecting the natural barrier system and its environment) and designing (a.o. developing the man-made barrier system, taking due account of the site characteristics) of a disposal system is to ensure that post-closure safety will be provided by means of multiple safety functions and that even if a component or safety feature does not perform fully as expected, a sufficient margin of safety will remain.