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EVOLUTION OF SAFETY STANDARDS FOR THE LONG-TERM MANAGEMENT OF NUCLEAR WASTE, AND THEIR APPLICATION IN ONTARIO POWER GENERATION

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ABSTRACT

This paper examines the need to develop current radiation protection methodologies further in order to take account of the special features of long-term waste management. The need to expand the scope and nature of regulatory submissions is also addressed. It is concluded that an international consensus is emerging as to requirements for a safety case for long-term waste management, and on safety assessment approaches and criteria to be applied in the regulation of long-term waste management facilities. The application of some of this methodology in preliminary concept assessments carried out by OPG for long-term waste management facilities is described.

1. INTRODUCTION

Used fuel and other radioactive waste from operation of Ontario Power Generation's (OPG's) nuclear reactors has been safely and responsibly stored at facilities adjacent to the power stations for the past 30 years. Solutions for dealing with the waste in the long term have been under development for a number of years.

A federal environmental review of the Atomic Energy of Canada (AECL) concept for deep geological disposal of nuclear fuel waste was completed in 1998. The Nuclear Waste Management Organisation is now working to recommend an acceptable long-term management approach for used fuel, while a technical program for deep geological disposal is being maintained by OPG.

For low and intermediate level waste, a long-term management plan has been developed by OPG and the Municipality of Kincardine, under a Memorandum of Understanding signed in 2002. These wastes are currently stored at OPG's Western Waste Management Facility, located near Kincardine. The option now under investigation is construction of a deep geological repository.

Submissions for regulatory approval will be guided by Canadian Nuclear Safety Commission (CNSC) regulatory documents. In particular, G-320, currently under development, is expected to give guidance for safety assessment of long-term waste management.[1]

This paper describes and explores considerations that have influenced the development of safety standards for facilities for the long-term management of nuclear waste, and gives some examples, from OPG's programs, of the application of current radiation protection criteria.

The scope of this paper is limited to consideration of radiological impacts on humans. However, it should be noted that future assessments would include examination of chemically toxic impacts and of potential impacts on non-human biota.

2. CURRENT SAFETY STANDARDS FOR INTERIM WASTE MANAGEMENT

In common with nuclear reactors, waste management facilities in Canada are regulated under the Nuclear Safety and Control Act and regulations. CNSC approval requires, amongst other things, submission of analyses and arguments showing that the requirements of the Radiation Protection Regulations are satisfied for both workers and members of the public under normal and abnormal operating conditions, and under accident conditions.[2] These requirements are summarised in Table 1. Secondary criteria derived from the limits are also used in design.

Table 1: Regulatory Dose Limits[3]

Person	**Limit**
nuclear energy worker	100 mSv in 5 year period 20 mSv in 1 year period
a person who is not a nuclear energy worker	1 mSv in 1 year period
occupational and public exposure to radiation shall be kept as low as reasonably achievable	

Assessment of malfunctions and accidents for current facilities includes consideration of postulated external and internal events. These include potential leakage into groundwater. Because of the passive nature of the facilities, and the generally stable waste forms, dose consequences are very small, and well within annual regulatory dose limits.

These analyses are contained in the Preliminary Safety Analysis Report (PSAR) submitted to CNSC as part of the application for a Construction Licence (or Approval under an existing licence), and are updated and augmented with additional material, e.g. the occupational radiation protection information and assessment, for the Final Safety Analysis Report for an Operating Licence.

For current facilities, the results of safety analyses for normal conditions are complemented by ongoing occupational and environmental monitoring, confirming that radiological impacts are within limits and are as low as reasonably achievable.

3. SPECIAL CONSIDERATIONS FOR LONG-TERM WASTE MANAGEMENT

The operational phase of a long-term nuclear waste management facility, such as a deep geological repository, would include similar waste-handling activities to those at OPG's present facilities, and would be subject to the same radiological protection criteria and assessment methods. Novel activities such as transfer of nuclear waste underground would require particular attention from the viewpoint both of radiological protection and of conventional safety, but would benefit from experience in the mining industry, and from similar facilities in other countries.

In addition, long-term nuclear waste management requires consideration of time frames which, depending on the particular waste, may extend to 10^4 - 10^6 years. National and international policies and recommendations require that future generations are protected to the same level as current generations, expressed as follows in CNSC's Regulatory Policy P-290:[4]

> The predicted impacts on the health and safety of persons and the environment from the management of radioactive waste are no greater than the impacts that are permissible in Canada at the time of the regulatory decision.

Present storage facilities are designed to contain radioactive material and there are no significant emissions. In principle, extended storage could be carried out with continuing complete containment, although this option implies a need for periodic repackaging with concomitant risks and occupational exposure. It is expected that criteria for performance of such extended storage facilities would be similar to those applied to interim storage, however, special consideration of potential scenarios and events in the long term would be required.[5]

Other than disposal of small dilute quantities of radioactive materials by discharge to the environment, a "concentrate and retain" philosophy is also applicable to disposal, i.e. emplacement in a near-surface or geological repository with no intent to retrieve.[6] Facilities are designed with an initial period of complete retention within engineered barriers, during which time radioactive decay reduces the source term. For high level waste, this period is at least several thousand years.[7] However, in the very long term, it is not possible to assure continued isolation by engineered barriers. Safety assessment then focuses on predicting the potential course of mobilisation and movement of radionuclides out of a repository to the accessible environment, including transport through the geosphere in the case of a geological repository, with the attendant processes of delay, dilution, dispersal and absorption. The possible effects of inadvertent human actions on containment of waste have also to be addressed, for the period after knowledge of the repository and its contents is assumed to be lost.

There are clearly considerable uncertainties in assessing potential impacts in the time frames required. Many of the changes that will occur, such as changes in the biosphere and geosphere, can be covered to a large extent by considering a range of scenarios, for example by the examination of scenarios which include the effects of glaciation. Uncertainties remain, in the sense that the precise conditions associated with assessment of the movement of the radioactivity from the waste far in the future – geological and hydrogeological characteristics, waste and barrier chemistry, geochemistry, etc. - are not known Conservative assumptions for all parameter values would be unrealistic and could lead to incorrect choices of management method and design features. These factors can be addressed largely by choice of scenarios and by use of probabilistic assessment. However, it has to be recognised that doses can only be estimated, rather than predicted. In addition, it is not possible for the current generation to confirm the results of long-term analyses by monitoring.

While it is anticipated that the operational phase of a disposal facility, i.e. emplacement and closure activities, would be monitored and regulated in the same way as current facilities, assessment of the postclosure phase requires a review and reconsideration of radiological protection methodologies and criteria for ensuring protection.

4. EVOLUTION OF ASSESSMENT APPROACH FOR LONG-TERM WASTE MANAGEMENT

In the 1980s, publications by the International Atomic Energy Agency (IAEA) and International Commission on Radiological Protection (ICRP), together with the CNSC's Advisory Committee on Nuclear Waste report on radioactive waste disposal, suggested that it was desirable to obtain a comprehensive assessment of all scenarios in order to compare total future risk with a risk criterion.[8,9,10] This approach was incorporated in Atomic Energy Control Board (AECB) regulatory document R-104 (now withdrawn). Uncertainty was taken into account by using a conservative risk criterion, and by using probabilistic assessment with parameter ranges or distribution as an integral part of the analyses. Parameter distributions were thus used to account for two sources of uncertainty: natural variability and different future scenarios. This paradigm was in place during development of AECL's Environmental Impact Statement (EIS) on the concept for disposal of Canada's nuclear fuel waste.[11]

As national and international programs have advanced, it has been recognised that it is not possible to characterise completely all the possible pathways and scenarios by which exposure might occur, together with their probabilities. The aggregated approach, which aims at providing a risk number for comparison with a risk criterion, is also limited in the information it provides of the robustness of the disposal system. More important than an absolute calculation of risk is reassurance in the safety case that:

- the characteristics and behaviour of the disposal system, including the geosphere, are understood;
- the system has been designed, and the setting has been chosen, such that doses to the critical group, in the expected evolution of the repository, will be well within current dose limits, and
- uncertainties have been adequately taken into account in the safety assessment.

Recent international discussion has therefore tended to favour three components to the safety assessment:[7,12,13]

- Assessment of the most likely, or normal evolution scenario. Results of analyses are compared with a criterion derived from the public dose limit.
- Assessment of a limited number of less likely scenarios, including natural events such as seismic events, and inadvertent human intrusion events, such as drilling into a repository. Estimates of the likelihood of such events are considered together with estimates of dose to humans, or other indicators of safety, for use in determining the safety of the repository in a disaggregated approach. As for current facilities, a cut-off in estimated likelihood for events to be considered should be applied. Additional considerations such as the duration and extent of the calculated doses and risks may be useful in evaluating significance.
- Assessment of “what-if” scenarios, or failure modes, for example by assuming that a particular barrier behaves, in the long term, differently than expected. The purpose is not to estimate risk, but to explore the potential impact of uncertainties and of very unlikely events as an indication of the robustness of the repository design.

In this approach, the range of scenarios identified has to be sufficient to illustrate facility safety and robustness, but is not required to be complete.

As noted above, depending on the waste, the timescale of assessment may extend to very long times. An increase in uncertainty with time has been used in some assessments as a reason for ‘cutting off’ quantitative assessment at a particular time. US regulations for Yucca Mountain required quantitative assessment to 10^4 years; this has been the subject of a court challenge. AECB’s R-104 also required quantitative assessment to 10^4 years, with reasoned argument for time scales beyond that. In part, this choice of a limited timescales was based on reasoning that uncertainties would increase abruptly beyond the next glaciation. However, it follows from the need to protect future generations that the behaviour of a disposal system and of eventual releases into the geosphere and/or biosphere should be examined and assessed over a timescale sufficient to include the time of peak impact, while recognising increasing uncertainty with time. Consistent with international discussion on this point, Regulatory Policy P-290 requires that:

> The assessment of future impacts of radioactive waste on the health and safety of persons and the environment encompasses the period of time when the maximum impact is predicted to occur.

Safety assessment of repositories for long-lived waste therefore involves dealing with the uncertainties implicit in long timescales. A particular major consideration in Canada is the onset of glaciation, which will change the surface environment and may change the parameters of the hydrological flow system important to the movement of radionuclides.

In recognition of the increase in uncertainty with time, the results from performance assessment are now recognised as indicators of safety (rather than as actual predicted impacts).[7,13,14] As an example, doses may be calculated assuming constant current conditions; although likely not realistic, this is a useful baseline analysis because it provides a consistent and familiar basis for comparison with present standards. In addition, in the long ($10^4 - 10^5$ years) and very long term ($>10^5$ years), these results may be increasingly supported, or substituted by, alternative indicators which have less uncertainty.[8,15] Thus, the strategy of the assessment may change with timescale. This may be recognised by defining specific time frames, or ranges, in which there are different expectations of the safety assessment, as in IAEA documents, and, more recently, in regulations for disposal of used fuel in Finland.[8,16,17] Safety indicators, such as fluxes through barriers, fluxes to the biosphere, environmental concentration, radiotoxicity indices, may be acceptable alternative end points for use at long times. These safety indicators have to be applied intelligently; for example, in comparisons of amounts of radioactivity, the radionuclide and its availability for release have to be considered.

In addition, and of fundamental importance, uncertainty in the long term is recognised in the safety case by development of a range of quantitative and qualitative arguments for safety.

5. THE SAFETY CASE

Application for regulatory approval for a long-term waste management facility is expected to follow the same processes as presently used for interim waste management facilities, described in Section 2 above. Additional material needed for the long-term facility is thus added to an established format. This material may include sub-surface site characterisation information and the post-closure safety assessment, together with, for a geological repository, discussion of mine safety and decommissioning and sealing of underground facilities. Because of the nature of the facility, the assessment of post-closure safety draws from specific regulatory guidance, and from international guidance and examples, in addition to maintaining consistency with methodologies for safety assessments for other waste management facilities.

The quantitative safety assessment, which is itself multi-component, as detailed in Section 3 above, is compiled together with complementary safety arguments to present a long-term safety case for the repository. In this context, the safety case is defined as the collection of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the radioactive waste disposal facility.[12] Examples of potential complementary safety arguments are shown in Table 2.

Table 2: Examples of Complementary Arguments for a Post-Closure Safety Case

- Natural analogs for the behaviour of components of the repository system, e.g. corrosion of materials used in containers; long-term stability of uranium deposits
- Long-term stability of the host geological formation
- Robustness of the disposal system design
- Stability of materials in the geochemical conditions of deep groundwaters
- Stability of waste form
- Mitigating effect of repository chemical conditions
- Paleohydrogeological evidence for the age of groundwaters and of their slow movement (or stagnation)
- Evidence for diffusion-dominated conditions in the repository location
- Studies and research supporting the choice of scenarios for assessments
- Studies and research supporting the role of sorption and diffusion in limiting radionuclide movement
- Natural processes of solubility control
- Use of different, independent models for assessment (e.g. simple, complex, different representations)
- Radiotoxicity arguments
- Intrinsic safety, based on favourable geological characteristics
- Alternative indicators of safety

Another characteristic of the long-term safety case is that, because of the need for projection into the future, the usual level of certainty in estimates of impact is not achievable. ‘Reasonable assurance’ (or a ‘reasonable expectation’) that radiation protection objectives are satisfied is required, and can be obtained by use of careful, reasonably-conservative estimates, supported by multiple lines of reasoning, as described above. This approach recognises that dose estimates are not predictions of future health detriment but are safety indicators, as noted in Section 4 above. This evaluation philosophy has been outlined by international bodies, and in the US is specified in NRC regulations.[13,14,18]

6. RADIATION PROTECTION CRITERIA

The basic radiation protection criterion in AECB’s R-104 was a requirement that the predicted radiological risk to individuals should not exceed 10^{-6} fatal cancers and serious genetic effects per year. This criterion of 10^{-6} per year took account both of uncertainty and of potential multiple sources. The same criterion is still part of several national programs. However, the difficulty of calculating the “sum over all scenarios” may be a distraction from the real issues such as ensuring robustness of the analysis. Recent publications have favoured a more transparent assessment which explicitly takes uncertainty into account, and which addresses a range of scenarios in a clear manner.

Criteria have moved towards a single dose constraint for normal evolution, together with allowance for a risk sum to be used to take account of less probable events.

National criteria recently compiled by NEA for the normal evolution scenario for long-lived waste are summarised in Figure 1. For this figure, the values for the UK and Sweden are derived from a risk limit of 10^{-6} per year using risk coefficients specified in the corresponding guidance. It may be noted that the resulting expectation values of dose are close to the value of 10 μSv considered in deriving clearance levels for removal of materials from regulatory concern.[19,20]

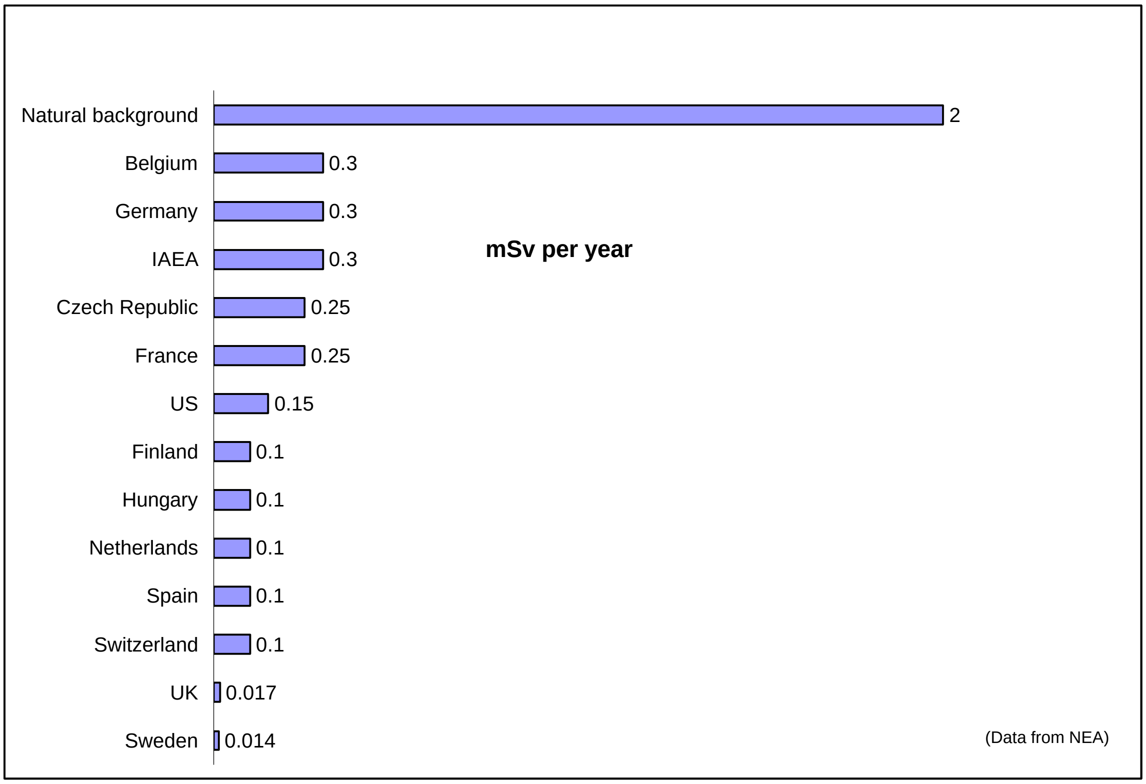

Figure 1: National and International Criteria for Disposal of Long-lived Waste (Normal Evolution Scenario)

Following withdrawal of R-104, OPG's recent assessments have used criteria based on the recommendations of ICRP Publication 81.[13] ICRP's advice for disposal of radioactive waste has been developing since 1985. The system is one of constrained optimisation. That is, during design, reasonable means of reducing predicted doses further are investigated, however, the design must in any case meet the dose constraint. The recommended dose constraint has remained essentially unchanged in this period at a fraction of the recommended public dose limit (e.g. 0.3 $mSv \cdot a^{-1}$), or the risk equivalent for probabilistic events. However, in ICRP 81 their advice has been made more explicit, particularly for human intrusion, and advice on criteria for probabilistic events now favours the disaggregated approach described in Section 3 above.[13]

As noted, human intrusion is addressed explicitly in ICRP 81, where it is stated that human intrusion is not part of the expected or natural evolution of the system and the consequences should be judged differently. However, for some wastes, intrusion could potentially lead to relatively high doses to future individuals. ICRP recommend that, to evaluate the resilience of a repository to such events, the consequences from one or more plausible stylised scenarios should be examined. Rather than applying a dose or risk constraint, the criteria used to judge whether the consequences are acceptable should be those currently recommended for use in remedial situations, where it has to be decided whether an intervention to reduce dose would be of net benefit in a particular situation. Thus, consistent with earlier ICRP advice on potential dose, ICRP 81 recommends that, as a measure of significance, an annual dose of around 10 mSv is a level below which no optimisation (or demonstration of ALARA) is needed. This value may therefore be seen as an acceptable level. Optimisation should be applied when predicted doses are between 10 $mSv \cdot a^{-1}$ and 100 $mSv \cdot a^{-1}$.[13] This implies that dose above 100 $mSv \cdot a^{-1}$ would be unacceptable.

Optimisation with regard to intrusion might include reducing the likelihood of intrusion events using methods reasonable in light of the estimated doses, such as siting a repository at depth, siting away from ore bodies, incorporating robust design features which make intrusion more difficult (such as provision of thicker engineered barrier materials), employing active institutional controls (such as monitoring for potential releases or restricting access) and passive institutional controls (such as records and markers).[13] It must be noted that the concept of geological disposal already incorporates such features, notably removal and isolation of the waste far from the accessible environment, which reduce the probability of any dose being incurred.

Collective dose is not seen by ICRP as a useful criterion for radioactive waste disposal, because of problems in assessing collective dose over long time periods in the future. However, consideration of the number of people involved and the distribution of doses in time may add information for use in assessing the safety of a facility.[13]

7. APPLICATION OF SAFETY STANDARDS IN RECENT ASSESSMENTS

Two recent assessments, OPG's Third Case Study for disposal of used CANDU fuel in a deep geological repository, and a preliminary safety assessment of concepts for Low Level Waste (LLW) at the Western Waste Management Facility, carried out by Quintessa[21,22,23] are used as examples to show how criteria for long-term safety have been applied in OPG's programs. These assessments followed an approach consistent with best international practice as developed under the IAEA ISAM program (Improvement of Safety Assessment Methodologies). This involves identification of assessment context, system description, development and justification of scenarios, formulation of models, analyses and interpretation of results . Both assessments are preliminary; in the case of the Third Case Study, exploration of the methodology was an important part of the objectives.

As part of context-setting, criteria were defined based on the recommendations of ICRP.[13] In the assessment of normal evolution, the ICRP dose constraint of 0.3 mSv per year was used to judge the potential acceptability of the concepts. However, in the Quintessa study, the criteria for human intrusion considered were slightly more restrictive than those recommended in ICRP 81. This variation was adopted because the current CNSC regulations suggest the need for action if potential exposures could exceed the annual public dose limit of 1 mSv (see Table 1). A more cautious approach was therefore used in the study, with a criterion of 1 mSv rather than 10 mSv as an indication of acceptability, pending further guidance from the CNSC. (For the near-surface concepts included in the study, the likelihood of intrusion might be considered higher than for a deep geological facility, over the relevant time period of many thousands of years.)

For the LLW deep geologic repository concept, the calculated dose rates in the Quintessa study were below the criteria by many orders of magnitude for both normal evolution and human intrusion scenarios. In the Third Case Study for used fuel, calculated dose rates for the normal evolution scenario were also below the criterion by many orders of magnitude. A drilling scenario analysed to examine the potential effects of human intrusion led to potentially significant doses, because the natural and engineered barriers were bypassed and humans came in direct contact with the used fuel. Taking into consideration the calculated doses, and the range of likelihoods and number of people exposed, it was concluded that while human intrusion could lead to appreciable doses to a small number of people near the repository site at times up to around 1000 years post-closure, the likelihood of this exposure was very small.

Certain "what-if" scenarios were examined in the Third Case Study, for example failure of all containers simultaneously at the design lifetime of the container, a high uranium solubility, and low sorption in the geosphere. All calculated doses were below the ICRP criterion for normal evolution, indicating a high degree of robustness in the reference design.

The Third Case Study also examined alternative indicators of safety – radiotoxicity fluxes into the biosphere, and radiotoxicity concentrations in the biosphere. All indicators showed a large margin of safety.

It may be noted that OPG's geoscience work program in support of used fuel long-term management includes modelling and data development for safety assessment, and also work in understanding geological and hydrogeological systems which will contribute to complementary and supporting safety arguments as outlined in Table 2.[24]

Since specific regulatory guidance is under development by CNSC[1], any conclusions drawn from these assessments are preliminary. In addition, for both cases, reiteration of the safety assessment using data from site-specific characterisation and design will be needed, together with the preparation of supplementary analyses taking account of additional factors, prior to any licensing submission.

8. CONCLUSIONS

This paper has reviewed the developments that have taken place in radiation protection methodologies in order to take account of the special features of long-term waste management. The need to expand the scope and nature of regulatory submissions has also been addressed. It can be concluded that an international consensus is emerging as to requirements for a safety case for long-term waste management, and on safety assessment approaches and criteria to be applied in the regulation of long-term waste management facilities. Some of these tools have been applied in preliminary concept assessments carried out by OPG, and, pending the development of specific regulatory guidance, are available to be applied as part of programs moving towards seeking acceptance and approval for these facilities in a future site-specific context.

Developing a technically defensible approach to post-closure assessment has been a lengthy and iterative process. A future challenge is to apply it to the satisfaction not only of the regulator, but also of other interested parties.

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