AN INTEGRATED SAFETY APPROACH AND CONSIDERATION OF SOME BASIC CRITERIA FOR THE DISPOSAL OF RADIOACTIVE WASTE

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Abstract

According to Swedish regulations the nuclear power plant owner is responsible for the safe management and disposal of radioactive waste. Criteria for protection of health and environment are set by the Swedish Radiation Protection Institute (SSI). The Swedish Nuclear Power Inspectorate (SKI) sets corresponding safety criteria and is responsible for review and supervision of the safety of facilities for management of nuclear waste, the nuclear industries R&D programme and the funding system for future costs for nuclear waste disposal. All of these tasks of SKI include assessments of safety.

An assessment of the safety of final disposal of radioactive waste should cover the total disposal system (all barriers of the repository system; operational phase as well as post-closure phase of the repository).

Each step in a handling sequence must consider earlier as well as subsequent steps, so that a waste product resulting from one step is suitable for all subsequent steps.

The safety of a repository for high level waste and spent nuclear fuel should rely on a robust system of multiple barriers. The application of this principle means that the function of one of the barriers might be lost without seriously jeopardizing the safety. Deep geological disposal seems to be the only option available today which complies with this requirement. Even if the assessment relies on an assessment of the total system and not on technical subsystems, technical requirements on the individual barriers must be defined.

The safety case is defined by a set of scenarios. Also possible human actions that could affect the integrity of the repository system should be included. A safety assessment includes an uncertainty analysis of models, scenarios and data. The need for verification/validation of models and the reliance on expert judgement is pointed out as well as the need to accept "reasonable assurance" as the realistic attitude in the demonstration of safety.

Roles of the operators and authorities in Sweden

Operators have a cradle-to-grave responsibility for the environmental effects of their activities. Authorities regulate and monitor those activities, but should not take over the operators' responsibilities.

In Sweden the regulatory system very clearly assigns the responsibility for all measures for the safe management and disposal of nuclear waste to the nuclear plant owner, the waste producer. Occupational and public health and environmental preservation during all phases of nuclear power operation, including waste management and disposal, must conform with criteria which the Radiation Protection Institute (SSI) sets in accordance with its task to protect man and the environment against harmful effects of radiation. The Swedish Nuclear Power Inspectorate (SKI) sets corresponding safety criteria for the technical performance of every aspect of nuclear power, including waste management, in accordance with its task to supervise that nuclear facilities and activities offer the needed level of safety and also the system for safeguarding nuclear material. These two authorities review and supervise facilities for management of nuclear waste according to their responsibilities. Furthermore, SKI reviews the periodic R&D programme of the nuclear industry that is required by law and supervises the funding system for future costs for nuclear waste disposal.

Basic criteria for the disposal of high level waste

International and national bodies setting criteria agree that in principle, waste management and disposal must correspond with the same safety and protection criteria as of other aspects of nuclear power operation. However, in the context of disposal of long-lived waste, the possibility of potential future exposures complicates assessment. For long time scales, conventional radiation dose criteria must be supplemented, e.g. with criteria addressing release of activity.

The International Commission on Radiological Protection (ICRP) has set fundamental criteria for practices involving radiation, viz. that the practice must be justified, and that concomitant doses must be optimized to be as low as reasonably achievable and in any case below specified dose limits (1). These criteria apply also to management and disposal of waste, although such activities would normally automatically be justified once the practice generating the waste is permitted. However, after closure, a repository for deep geological disposal will not generate any doses at all, if a complete isolation of the waste is achieved. Thus, optimisation and dose limitation must address potential exposures due to unscheduled events, possibly in the far future, as envisaged by ICRP (2). ICRP has developed the concept of potential exposures further (3), albeit not primarily with a view to long-lived waste. It is understood that the possibility of providing further guidance on waste management questions is under discussion within ICRP.

The International Atomic Energy Agency (IAEA) has issued Safety Standards covering basic requirements on radioactive waste management addressing e.g. protection of human health and the environment, the need for establishment of national regulatory systems for radioactive waste management including the need for laws, a clear definition of roles between regulator and implementor, QA-systems etc (4, 5). The OECD/Nuclear Energy Agency (NEA) has published several documents on waste management issues, e.g. collective opinions by experts on final disposal addressing the possibilities for evaluation of the long term safety of disposal of radioactive waste (6) and on the environmental and ethical basis of geological disposal (7). The collective opinion is that the long term safety can be evaluated and that there is an environmental and ethical basis for acceptance of geological disposal.

These publications reflect different aspects of radioactive waste management. Basically they are not in conflict with each other, but should rather be seen as complementary. Various national organisations have also published recommendations and statements. For instance, in 1993 the Nordic Safety and Radiation Protection Authorities published a document on "Disposal of High Level Radioactive Waste. Considerations of Some Basic Criteria" (8). This document is also in agreement with the views of international organisations as referenced above. The recommendations in the Nordic document are presented here as a rather extensive and fairly operational set of criteria.

Summary of main guidelines and recommendations considered by the Nordic Safety and Radiation Protection Authorities

General objective
The disposal of high level waste shall aim at protecting human health and the environment and at limiting the burdens on future generations.

Long term safety
The risk to human health and the effects on the environment from waste disposal, at any time in the future, shall be low and not greater than would be currently accepted. The judgement of the acceptability of a disposal option shall be based on radiological impact irrespective of any national boundaries.

Burden on future generations
The burden on future generations shall be limited by implementing, at any appropriate time, a safe disposal option that does not rely on long term institutional control or remedial actions as a necessary safety factor.

Justification of practice
No practice involving exposure to radiation should be adopted unless it provides sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes.

Optimisation
Radiation protection related to waste disposal shall be optimised. In doing so, radiation and risks must be compared and balanced against many other factors that should influence the optimised solution.

Individual protection
Up to reasonably predictable time periods, the radiation doses to individuals from the expected evolution of the disposal system shall be less than 0.1 mSv/year. In addition, the probabilities and consequences of unlikely disruptive events shall be studied, discussed and presented in qualitative terms and whenever practicable, assessed in quantitative terms in relation to the risk of death corresponding to a dose of 0.1 mSv/year.

Long term environmental protection
The radionuclides released from the repository shall not lead to any significant changes in the radiation environment. This implies that the inflow of the disposed radionuclides in the biosphere, averaged over long time periods, shall be low in comparison with the respective inflow of natural alpha emitters.

Safety assessment
Compliance of the overall disposal system with the radiation protection criteria shall be convincingly demonstrated through safety assessments which are based on qualitative judgement and quantitative results from models that are validated as far as possible.

Quality assurance
A quality assurance program for components of the disposal system and for all activities from site confirmation through construction and operation to closure of the disposal facility shall be established to achieve compliance with the design bases and pertinent regulations.

Multibarrier principle
The long term safety of the waste disposal shall be based on passive multiple barriers so that deficiencies in one of the barriers do not substantially impair the overall performance of the disposal system and so that realistic geological changes are likely to only partly affect the system of barriers.

The Swedish regulatory authorities, SKI and SSI, are now developing national regulations based on the Nordic document and on other relevant documents, *inter alia* publications by ICRP, IAEA and OECD/NEA.

No technical subsystem criteria are defined by the authorities. This would restrict the possibilities of the nuclear power plant owners to shoulder the responsibility given to them by Swedish law to take all necessary actions to ensure safety.

Demonstration of compliance with criteria

Criteria and regulations should be formulated in such a way that compliance can be demonstrated.

Criteria and regulations should aim at defining a required level of safety but in order to be useful they must be set up in such a way that compliance can be demonstrated by accepted methods of assessment. The very long time perspectives in final disposal of HLW and spent fuel will lead to large uncertainties in the assessments. This is a difficulty but does not change the principal requirements on evaluation and demonstration of compliance with given criteria.

Criteria and safety assessments will normally be of both qualitative and quantitative nature. Even such safety assessments that are presented in a quantitative form will to a great extent be based on understandings of qualitative nature (expert judgement). Given the qualitative elements of safety assessments the demonstration of compliance will never be very precise. Reasonable assurance is however required.

Performance assessment as a regulatory tool

Performance assessment methods offer a possibility to assess a technical system in a comprehensive manner. They may be used for assessing safety, identifying R&D needs and may also be valuable as a background for calculating costs for future radioactive waste management.

In order to fulfill their obligations as producers of waste, the nuclear power plant owners have formed a joint company, the Swedish Nuclear Fuel and Radioactive Waste Management Co (SKB), to construct and operate radioactive waste management facilities and to perform the necessary R&D work. The responsibilities given to the nuclear power plant owners and to SKB put a demand on competence and resources. The regulations require the safe operation of facilities, but also the presentation of a comprehensive R&D programme to cover e.g. storage and disposal of spent fuel every third year, and also a funding system to cover the future costs for spent fuel management and disposal. It is very evident that the nuclear power plant owners and the SKB need to have competence in evaluating the safety of nuclear waste facilities and practices. SKB has spent a lot of efforts in developing competence in performance assessment methodology and continues to do so.

Also a regulatory authority in the field of radioactive waste management needs to have competence and tools for evaluating safety and radiation protection. The Swedish Nuclear Power Inspectorate has since many years engaged itself in competence building in performance assessment methodology. SKI as a matter of fact regards performance assessment methods as a regulatory tool to be valuable in the review and assessment of disposal concepts presented by SKB. This will be even more valuable in the expected license application for the encapsulation facility for spent fuel and the deep geological repository. An application will, according to SKB's plans, within a couple of years be submitted to SKI and referred for comments to SSI and other authorities.

Performance assessment methods may also be valuable in identifying needs for improved understanding. This may be achieved through uncertainty and sensitivity analysis. SKI has recently concluded a performance assessment project addressing the safety of a deep geological repository for spent fuel (SITE-94) (9) and earlier an effort of the same character (Project-90) (10). Project-90 was based on data for a hypothetical site for a deep geological repository for spent fuel. The geological data were chosen to be representative for Swedish geology. In the SITE-94 project real geological data from an actual site (not intended for a repository) was used. The intention with these projects have been to increase the competence of the SKI and to prepare for coming licence applications. The two projects have clearly demonstrated the usefulness of performance assessment methods as a regulatory tool.

The Swedish Radiation Protection Institute is engaged in problems of optimisation under uncertainty. Disposal of high level radioactive waste constitutes an extreme case where hypothetical, potential future exposures of "the public" (which may no longer be formed of humans!) must be balanced against current occupational exposures of the public due to accidents before closure of a repository. Obviously, no single calculation could lead to a definitive answer to this problem. However, SSI is currently concluding an environmental impact assessment project called MKB-95 (11). This has resulted in a computerised tool aimed at sensitivity analyses, so as to illustrate the effects of changing assumptions and parameters in the optimisation process.

Performance assessment methodology is valuable in many respects. It's essential in verification and validation of models of the system. It's valuable in understanding how scenarios and time frames for assessing a repository system should be formulated. It can give quantitative results on the long term performance of a repository as a radiation dose or as an indicator of safety in the very long time perspective. It is needed in the definition of technical requirements on the canister for HLW or spent fuel. Above all it is useful in assessing the long term impact on the environment from a repository system. It must always be born in mind, however, that the quantitative results are to a very great extent based on qualitative evidence, expert judgement etc.

Total systems assessment

The ultimate goal in assessing safety is to cover all aspects of risk. All phases in the development of a waste management system should be evaluated. All facilities and practices being part of the system should be evaluated. In a repository system the total system including all barriers must be evaluated. Also the consequences of human intrusion into a repository should be evaluated.

A complete system for the management of radioactive waste and spent fuel from a nuclear power programme consists of many different activities; e.g. handling, treatment, storage, transport and disposal. Most of these activities require specially designed facilities. It is quite obvious that radiation protection and safety aspects have to be identified and analysed in all these activities and related facilities. The character of risk may differ considerably between e.g. storage and transport but the need for evaluation will always be there.

Some of the effects of waste management will occur during the operation of waste management facilities (doses to workers handling the waste) and some effects may occur in the very far future (during the post closure phase of a deep geological repository). Doses during the operational phase can be monitored and controlled. The potential doses from the post closure phase of a deep geological repository will occur in the very far future and we can not rely on monitoring and control. The system must be so designed that we have confidence in its long term behaviour. However careful we are we must accept that uncertainties exist. The proper balance between risks today (possible to monitor and control) and risks in the very far future (for which we can have no reliance on monitoring and control) is a difficult matter involving not only the uncertainties in the technical system but also philosophical and ethical aspects.

Interdependencies

A waste management system can be subdivided in separate parts and steps. It may be valuable to assess individual parts separately. In evaluating a separate step it must however be recognized that the following steps may be effected by preceding steps. This fact should also be observed in the decision process. A decision may partly or strongly be binding for the following steps.

The management system for nuclear waste, especially HLW and spent fuel, will be a complex system of activities and facilities of sometimes very different character. It is necessary to see the system as being built up by individual parts. Otherwise it will not be possible to plan and construct individual facilities being parts of the total system. In doing so it must however be remembered that these activities and facilities are parts of a total system. This means that interdependencies between all these parts have to be assessed. During the planning and construction phase performance assessment and planning activities will form an iterative process. One example of these interdependencies is the Swedish programme for spent fuel disposal which includes an encapsulation facility for spent fuel and a deep geological repository. In planning for the encapsulation plant it must be remembered that the canisters for spent fuel produced in this facility will eventually be disposed of in the repository. It is quite evident that the canisters must fulfill the requirements given by the repository system. Decisions on the encapsulation plant can not be taken without consideration of the deep geological repository. In some degree of detail the total system (encapsulation facility, canister, geological repository etc) must be assessed (12).

Another example may be the Swedish repository for nuclear waste (intermediate and low level waste) from the operation of the nuclear power plants; the SFR facility, near the Forsmark nuclear power plant. Waste types already produced existed when the repository was planned. The repository thus had to be designed to be able to accept these waste types. New waste types have to conform with the given design of the repository (13).

The effects on the decision process must be observed. A decision to design and construct a facility, e.g. an encapsulation plant, will influence the subsequent steps, e.g. a repository. The level of freedom to take further decisions on the disposal system will decrease. Decisions on individual parts of the disposal system will also influence future costs for the remaining parts and for the total system.

Deep geological disposal

Deep geological disposal of HLW and spent fuel is judged to be justified both from an environmental and ethical point of view.

It is not possible to rely on institutional control of storage for high level waste or spent fuel for very long time. A more reliable solution is needed. Deep geological disposal is the preferred option for high level radioactive waste and for spent fuel. Even if no repository for HLW or spent fuel is yet in operation, this option is under development in many countries. The Radioactive Waste Management Committee (RWMC) of the OECD/Nuclear Energy Agency (NEA) has in a recent statement declared that it is justified, both environmentally and ethically, to continue the development of geological repositories for long-lived radioactive waste (7).

Deep geological disposal typically means a repository excavated in a geological formation (e.g. crystalline rock, salt or clay) at the depth of several hundred meters. The HLW or the spent fuel is encapsulated in long-lived canisters which are deposited in repository. No long-term surveillance is required. Institutional control may however be performed for some period of time.

The reason for choosing deep geological disposal is the reliance we can put on the long term stability of the geology at a carefully chosen site. Arguments for this has recently been given by the NEA, mentioned above, and by the US National Academy of Sciences (14) in its report on the Yucca Mountain project. The SKI and SSI also share this view.

There are however other views. Some experts may find it too early to take decisions on final disposal as alternatives may be available in the future. One example of this is partitioning and transmutation of long-lived radioactive waste, a technique that may transform longlived radionuclides into less harmful nuclides. This will require a lot of work and time and there is no guarantee for success, that is an overall reduction of risk at a reasonable cost. In the NEA statement it was made clear that from an ethical standpoint, geological disposal is preferred over long term storage (waiting for new solutions) which requires long term surveillance.

Multibarrier system

Taking into account the very long-term perspectives and the uncertainties associated with the safety of a repository for long-lived waste, e.g. spent fuel, a robust system is needed. A repository built up by multiple barriers offers a more robust system than a repository relying essentially on a single barrier.

Final disposal of radioactive waste puts demands on the repository system. The intention with a repository system is to isolate the radionuclides and to restrict the release if and when releases occur. For HLW and spent fuel the relevant time perspectives for the functioning of the repository will be in the order of hundreds of thousands of years and more. Even if the geological environment will be stable for very long time periods it is evident that uncertainties in the evolution of the repository system in the long term may be great e.g. because of climate changes and human actions.

A quotation from the Nordic document (8) reads:

"The long term safety of the waste disposal shall be based on passive multiple barriers so that deficiencies in one of the barriers do not substantially impair the overall performance of the disposal system and so that realistic geological changes are likely to only partly affect the system of barriers."

The system should not rely on one single barrier but rather on a set of barriers that together offer a system robust to degrading mechanisms of different kinds, release and transport of radionuclides and to disruptive events. All this is best achieved with a multibarrier system comprising for example the spent fuel matrix, a long-lived canister, back-fill around the canisters in the repository and the geological medium itself. The process for transportation of radionuclides from the repository is dominated by groundwater transport. The depth of the repository must be sufficient to withstand erosion, glaciations etc. A sufficient depth also helps in protecting the repository against possible human actions.

The safety case

To define the safety case for disposal of long lived waste the disposal system and the features, events and processes affecting the system have to be defined. Normally this is done in terms of defining a set of scenarios.

In order to assess a disposal system and to see if regulatory criteria can be met, it is necessary to define the system. In the case of a repository the multibarrier system must be defined. The different barriers (waste matrix/spent fuel, canister, back-fill, geological medium etc) and their properties must be described. Also the system boundaries must be defined. The behaviour of the system is affected by features, events and processes (FEPs) within the system but also external FEPs may influence the system. The exact definition of the boundaries is a matter of judgement. Normally climatic changes, major disruptive event (e.g. faulting) etc are regarded as external FEPs.

The development of the repository system can not be observed and verified in the very long time perspective. A basic understanding of the system and the FEPs that may affect the system is needed.

FEPs affecting the system are normally combined and described as a scenario. Different combinations constitute different scenarios. Because of the uncertainties, mainly due to the very long term perspectives, a set of scenarios is needed to cover the development of the repository system.

Safety assessment and uncertainty

Safety assessments for very long term periods will always be uncertain. If we know and understand the reasons for uncertainty and if we can quantify the uncertainty much is achieved in assessing safety.

Safety assessment methods for the normal operation of a nuclear facility can be based on actual experience and statistics. In addition to deterministic evaluation, probabilistic methods utilising existing data can be used. Corrective measures can be initiated if needed. This also includes a repository in its operational phase (before closure).

For the post-closure phase of a repository, monitoring and control are not possible in the very long time perspectives. Assessments must be based on a genuine understanding of the repository system and its environment, including also the development of the system in the very long term perspective. The underlying knowledge base is both of qualitative and quantitative nature.

The definition of the safety case can be seen as a part of the safety assessment. Other parts are then related to the modelling and consequence analysis.

Modelling includes the formulation of conceptual models of the disposal system (e.g. the repository and the geologic medium) and the translation of the conceptual models to computer codes. The input to the codes and the output are quantitative. If the models and the codes are good representations of what they are supposed to represent then the results will be good representations of the consequences. Are the models and codes good representations? This is a key question. Much effort has been spent on development of performance assessment methodology. Despite the difficulties there is confidence in the possibility to evaluate long term safety. Expert committees of the NEA, IAEA and the European Communities in 1991 (6) stated as a collective opinion that long-term safety in radioactive waste disposal can be evaluated.

As mentioned earlier the uncertainties in the safety assessments increase with time. This issue has been discussed in an IAEA document that also addresses the concept of safety indicators (15). It should be remembered that already in time perspectives of a hundred to a thousand years considerable changes in climate, living habits etc may occur. The quantitative results should for the long time perspectives not be regarded as exact representations of the effects on human health and the environment but rather as indicators of safety. Even if this is true, calculations covering long time periods are meaningful for certain purposes, such as ranking of alternative disposal options. The quantitative assessments will help in understanding the uncertainties and sensitivities in different parameters and couplings of processes within the system, and will thus help in understanding the long term behaviour of the system. A good understanding of the long term behaviour of the system is expected to be of value also for understanding of shorter time periods. For the performance assessment of the repository system, it appears that the inevitable cut-off in time should come considerably later than the time frame (say, 10 000 years) over which calculations of doses to humans retain any relevance. This view is supported by the fact that releases from a deep geological repository may increase and peak well beyond 10 000 years. It is however important to keep two things in mind: the results from calculations for such long time periods should not be regarded as a true representation of risk but rather as indicators of safety; and the risk associated with releases of long-lived radionuclides well after the short-lived gamma emitters have decayed should be compared to risks associated with stable chemotoxic nuclides.

Conclusions

In the development and review of a system for waste management and disposal it is necessary to assess the total system. All phases should be analysed: treatment, storage, transport, deposition of waste and the long term safety of the repository after closure. The complete repository system should be assessed including man made structures and the geological environment and the biosphere.

A well organised and well structured comprehensive assessment of the waste management and disposal system is very useful in relation to defining scenarios and time frames for evaluation of the repository performance as well as in defining technical criteria for selection of a repository site. It will also be valuable in defining the technical criteria for a canister for spent fuel or high level waste. Performance assessment methods will make it possible to evaluate the long term performance of a system for final disposal of radioactive waste.

It should always be born in mind, however, that the quantitative results from performance assessment calculations to a great part are based on evidence of qualitative nature. For the long term the results from performance assessment calculations should be regarded as indicators of safety rather than exact representations of risk.

From a regulatory perspective performance assessment methods are very useful and needed in understanding if a proposed system complies with given criteria. The answer to this may not always be simple but reasonable assurance is needed.

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