NORDIC CRITERIA FOR DISPOSAL OF HIGH LEVEL WASTE IN THE PERSPECTIVE OF INTERNATIONAL DEVELOPMENT IN THE AREA

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ABSTRACT

An overview of the international development of basic criteria for disposal of high level waste shows how the solution of many conceptual, philosophical and other problems are born, diverge and converge and how ideas are transferred between various international and national documents in order to harmonize. But there are still some unclear concepts and issues to be developed. The Nordic criteria will be published this year and they constitute another step forward in this area taking account of international discussions but also they have stimulated discussions during the production with some innovative ideas.

INTERNATIONAL DEVELOPMENT

The development of technique, management and criteria in the area of waste handling, storage and disposal has been remarkable during the last decades. In 60' ties and early 70' ties relatively little attention was given to the waste problems but the awareness increased in 70' ties and during the 80' ties the techniques as well as basic and applied criteria developed nationally and internationally. Simultaneously the public opinion turned to a more critical attitude and showed decreased confidence in the possibilities to solve the problems. This was particularly the case as regards the final disposal of high level waste (HLW).

One of the first international reports on the special problems connected with disposal of long lived radioactive waste is the report "Long-Term Radiation Protection Objectives for Radioactive Waste Disposal" by the Nuclear Energy Agency (NEA) of OECD, published 1984(1) Specific questions were discussed as limitations of individual dose or risk, the application of optimization of protection, the use of collective dose for future assessments, the possibilities of cut-off in time or dose and discounting in assigning monetary value of detriment.

Shortly thereafter ICRP published its publication 46, "Radiation Protection Principles for Disposal of Solid Radioactive Waste"(2). This publication was prepared almost in parallel with the NEA report and some of the members of corresponding expert group were the same. It is therefore not surprising that there are similarities in the basic philosophies. The concept of risk upper bound for a source like e.g. a waste disposal is recommended to be used. Probabilistic events and corresponding uncertainties and the genuine uncertainties about the future are discussed in relation to individual risk assessments stylized in mathematical formula and illustrated in graphical form like a criterion curve, that defines unacceptable region of probabilities and consequences. It is proposed that such a criterion curve can be used to illustrate the possible compliance with the risk-related requirements on a given waste disposal option. The principle of optimization should be applied but it is also clearly stated that it is only one input in the process of deciding a strategy and option for waste management and disposal. The ethical considerations in weighting the significance of future detriments are particularly emphasized.

The IAEA published already in 1983 a recommendations-report (3) on criteria for underground disposal of radioactive waste. It was followed up by an IAEA publication 1989 on safety principles and technical criteria for underground waste disposal (4) and account was then taken of the recommendations and discussions in the NEA and ICRP publications above referred to.

The IAEA report is written in terms of principles and criteria that can be traced back to the discussions of basic ideas in the NEA and ICRP publications. The overlying objectives of underground disposal is said to be to isolate the waste without relying on future generations and to ensure protection in accordance with current radiation protection principles. To meet these objectives a number of safety principles and technical criteria are formulated:

- the burden to future generations shall be minimized
- the safety shall not rely on institutional control
- there shall not be predicted future risks that would not be acceptable today
- the protection of people beyond national borders shall not be less stringent than for people within the borders
- the predicted annual dose to individuals of the critical group now and in future shall be less than a fraction of 1mSv
- the predicted risk of health effect in a year from disruptive events shall be less than a fraction of 10^{-5} per year
- all radiation exposures shall be as low as reasonably achievable (optimization)

Several difficulties are discussed briefly as e.g. the identification of the most highly exposed groups in the future and their habits. It is proposed that habits, lifestyles etc are the same as today. Another problem is the uncertainties in projecting future radiological impacts particularly in connection with an optimization process. It is proposed to handle the problems in a qualitative manner in combination with engineering judgements.

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The general principles are followed by a number of technical criteria including the multibarrier concept, requirements on the waste form, the repository, the site, safety assessments and quality assurance.

In a chapter called "other considerations" some Nordic ideas are mentioned briefly namely the comparison with natural radiation, flows and concentrations of natural radionuclides. These ideas are further developed into principles in the Nordic criteria document, se below.

In a joint Swiss - Swedish report, Regulatory Guidance for Radioactive Waste Disposal - An Advisory Document, published 1990 (5), some principles and problems are further discussed and developed. It is proposed that the dilemma of the uncertain repository system performances for long time scales is solved by scenario variation covering all realistically possible system evolution in the future. All models used for performance assessments of assumed systems should be validated. The problems with uncertainties of the evolution of biosphere and man are solved in a pragmatic way by assuming them to be the same in the future as today. As the doses are assessed for stylized scenarios there is no need for a time cut off but the doses should be assessed at least they have reached the peak values.

That the radiation environment of man should not be changed significantly is also here considered to be a reasonable requirement. The rationale is firstly that a minor change of radiation environment would not be considered unacceptable and secondly that if there is a change in biological sensitivity of future species, this relative change will be the same for the natural radiation as for the artificial caused by the radioactive waste and the relative increase of risk will consequently be the same as the relative increase of dose. The measuring stick for radiation environment is proposed to be in terms of toxicity or simpler total activity of alpha - emitters and beta/gamma emitters respectively. Annual release of toxicity or concentration in groundwater or soil may be compared with the corresponding natural radiation environmental quantities, for instance with the flow of natural radionuclides into the river that drains the repository region.

An important issue is emphasized by stressing the importance of transparency in the process of site selection, choice of repository design and assessment of performance and consequences. A major prerequisite (say major criterion) for the whole process is the public acceptance and for that it is essential to be transparent, i.e. to be clear, simple and conclusive.

The concepts dose limits and risk limits are also elaborated. Assuming risk is defined as the probability of event times the dose (Sv) caused by the event times the probability of death per Sv and an overall risk limit of $10^{-5} a^{-1}$ corresponding roughly to ICRP's dose limit of 1 mSv a^{-1}, the principle of apportionment leads to the recommendation that

- 10^{-5} should be the total maximum risk per year for an individual
- 10^{-6} should be the total maximum risk per year originating from one source
- 10^{-7} should be the maximum risk from a single event occurring at one source

For single events that are not infrequent (which in the report means more than 10^{-3} per year) this implies a corresponding dose upper bound of 0.01 mSv a^{-1} i.e. no credit shall be taken of the probability of the event. This can be done for events the probabilities of which are in the range of 10^{-7} - 10^{-3} per year. However an overriding requirement is that short consequence events giving rise to doses with deterministic effects ($\geq$0.5 - 1 Sv) shall not occur with a frequency higher than 10^{-7} per year.

There are also events where it is difficult to assign frequencies like human intrusion. In these cases risk limitation may not be the right tool for safety assessments but it is necessary to make a more qualitative judgement.

Another important publication in development of criteria for HLW disposal is the proceedings of a NEA workshop Paris 5 - 7 November 1990 named Radiation Protection and Safety Criteria (6). It gives a good overview of existing national and international approaches to the problems and the current status of guidelines and criteria. Individual dose limits or risk limits as safety indicators are generally in the range of 0.1 - 1 mSv a^{-1} or 10^{-6} - 10^{-5} a^{-1} respectively. Collective dose or risk limits are more used for comparison of repository design alternatives. Optimization is generally agreed as a principle but its application has to be adapted to what is achievable in practice. A similar level of safety should be provided for all future generations as that provided for the current generations. Other issues discussed in this report are risks related to human intrusion, flow of natural contaminants into the biosphere as safety indicator (Nordic approach), the need to cope with uncertainties in safety assessments, timeframes and possible cutoffs for formal requirements of quantitative assessments (10.000 years for some countries, one million years or even more for others). A special problem discussed in the report is how to demonstrate compliance with safety criteria. There is no straightforward answer to that question. It has to do with an understanding of the whole waste disposal system requiring high quality and good engineering practice throughout the whole process, using validated models and site specific data, make appropriate scenario selection and scrutinize the uncertainties.

A proposal that was made by one of us was that events with probabilities less than 10^{-6} a^{-1} as well as doses appearing after one million years should be ignored in the assessments and radioactive waste should be considered as a part of the natural environment after one million years. This thought was later followed up in the Nordic criteria.

In ICRP's new recommendations on radiological protection (7) radioactive waste problems are not particularly addressed but in the general system of radiological protection the optimization as well as dose limits principles now include the concept of potential exposure expressed as the likelihood of incurring exposures where these are not certain to be received should be kept as low as reasonably achievable and, respectively, the exposure of individuals should be subject to some control of risk in the case of potential exposure. A potential exposure is characterized by the uncertainty of occurrence and consequential detriments. It is commonly referring to an accidental situation but in case of radioactive waste disposal it also applies to the uncertainties associated with the long time performance of the repository, the environment and the recipients of activity and dose. Potential exposures may also lead to calls for intervention. However, in the long time perspectives that are considered the concept of intervention is hardly applicable in the way that the implication of intervention has to be accounted for. Instead the consequences of mishaps or accidents in the very far future have to be considered as such in a variety of scenarios and judged quantitatively and qualitatively.

Besides these international reports on development of criteria for disposal of HLW there are a number of national reports most of which are summarized in the Proceedings of the NEA workshop (6) referred to before. Some recent publications are the French Basic Safety Rules in 1991 (8) and a NRPB publication in 1992 on Radiological Protection Objectives for the Land-based Disposal of Solid Radioactive Wastes (9).

In the French rules ALARA is applied as a principle in the criteria of concept for the repository. The individual dose equivalents are limited to 0.25 mSv/year for extended exposure associated with events which are certain or highly probable. For a period of at least 10.000 years the stability of the geological barrier must be demonstrated. Beyond this time period the quantitative assessments may be supplemented by more qualitative assessments. The risk concept is introduced for potential exposure situations.

The basic radiation protection criteria are followed by safety related design basis including requirements on waste packages, engineered barriers, the geological barrier and the repository design. In a chapter on safety demonstration of the repository it is assumed that records of the repository would be kept for 500 years making human intrusion very unlikely. The rules are completed by requirements on quality assurance and a number of appendices on more technical matters.

In NRPB's statement on radiological protection objectives for land based disposal of solid radioactive waste it is recommended that future populations shall have an equivalent protection as that for populations today, that the radiological risk to a critical group, attributable to a single waste disposal facility shall not exceed the risk constraint of 1 in 100.000 per year and that ALARA principle should be applied.

These basic recommendations are followed by a keen analysis of the problems and limitations of application of the recommendations. It is concluded inter alia that if the individual risk to an average member of the critical group does not exceed a design target of 1 in 1 million per year then the optimization (ALARA) would be required only for the detailed design of the facility and not in comparison of various sites or options, that site-specific calculations relating to the biosphere and human behavior should not continue beyond about 10.000 years into the future and for times greater than that, reference models of biosphere and human behavior can be used in combination with constraints on radionuclide release rates from the geosphere, that site-specific calculations relating to the behavior of geological formations should not continue beyond about 1 million years into the future and for times after that only qualitative judgements should be made, that the total probability of occurrence for all naturally occurring events, that are likely to cause deterministic doses, should not exceed 1 in 1 million years, that risks should be ALARA and should be demonstrated by quantitative argument up to about 1 million years, after that by qualitative arguments only and that calculations of collective dose for input to optimization studies extending far into the future are not reliable and not recommended.

At present there is a development of basic ideas within a group of experts organized by IAEA in a Sub-group of INWAC (International Waste Management Advisory Committee). The issues that are discussed for the moment are inter alia dose versus risk, post-closure monitoring, safety indicators in different timeframes, the applicability of optimization, retrievability and safeguard in the context of waste disposal. This work is expected to analyze and hopefully clarify some of the issues that still are unclear and need to be developed.

THE NORDIC CRITERIA FOR DISPOSAL OF HLW

The overview of the international and national development in the area of criteria for disposal of HLW given above shows how ideas are born, developed and applied as criteria but in some parts still diverge in way of presentation, weighting of issues and in details. The Nordic countries have actively taken part in these discussions and already in 1987 a working group was convened with the purpose of producing a joint Nordic document on the subject. In 1989 a consultative document (10) was published and sent out to national and international organizations for comments. In 1992 a hearing was organized in Sweden and in 1993 the final version, that is presented here, will be published. In comparison with other publications there are many similarities, which is not surprising considering the mutual giving and taking of ideas in the international cooperation. To achieve similarities and harmonization is an objective in itself in an area with such international aspects as that of disposal of HLW and its long-time-perspective problems.

The Nordic document contains some descriptive chapters followed by the chapter 4 on regulatory requirements and recommendations, a chapter on site selection and one on research. In the following only chapter 4 will be summarized.

In a preceding explanatory text it is concluded that as radioactive releases into the environment are not expected until thousands or maybe even millions of years after the closure of the repository, it is not possible, in practice, to limit the releases by continuous control and monitoring of the source. Thus high confidence in the disposal system is required before disposal can be implemented.

The principles of individuals' protection may be applied to waste disposal in a similar way as made today in the timeframe which is reasonably predictable, perhaps up to some thousands of years. But in the far future beyond 10 000 years, the situation is somewhat different. The definition of the most exposed individuals is difficult as their characteristics, habits and living conditions cannot be predicted. A complementing approach is to limit societal radiological impact. This may be expressed in terms of collective doses or risks or other indicators of total radiological impacts.

It is advisable to complement the existing radiation protection principles by one which ensures that the total radiological impact of the disposal of high-level waste is small in comparison with the corresponding impact of the natural radionuclides. Collective doses are very sensitive to biospheric uncertainties, and are thus not ideal as measures of harm in the assessment of far future radiological impacts from waste disposal. As the geological environment is considered to be more stable than the biosphere an alternative approach might be to compare the release rate of the disposed radionuclides from the geosphere to the biosphere with the respective flows of natural radionuclides.

In the very far future, beyond millions of years, the total activity inventory of a high-level waste repository (around 1000 TBq) is less than that of a uranium ore deposit. The average inflow of radionuclides from a repository to the biosphere will also be less than that from many uranium ore deposits and below any reasonably constraints. Thus, a repository of high-level waste can be regarded to be analogous to natural deposits after millions of years and assessments of radiological impacts need not be extended beyond that time.

A. General considerations

General objective:

The objectives of disposal of high-level waste shall be to protect human health and the environment and to limit burdens placed on future generations.

Objective 1: Long-term safety

The risks 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 acceptable. The judgement of the acceptability of a disposal option shall be based on radiological impacts irrespective of any national boundaries.

Comments: Acceptable risk of death is a controversial issue. It varies between 0.1 - 1000 per million years depending on if it is the society or the individual that are concerned, voluntary risks or not etc.

Some very long-lived radionuclides may disperse even globally and build up in the environment during long time periods. To avoid unacceptable build up of radionuclide concentrations in the environment, the cumulative effect of all waste repositories must be taken into account.

Objective 2: Burden on future generations

The burden on future generations shall be limited by implementing at an appropriate time a safe disposal option which does not rely on long-term institutional controls or remedial actions as a necessary safety factor.

Comments: Since the present generation mainly benefits from the exploitation of nuclear energy, it is reasonable that it should bear at least the financial burden of waste disposal. This economic burden should correspond to the efforts needed to reduce the future radiological burden to an acceptable level, as it is judged currently.

The timing of the implementation of waste disposal depends on a number of factors. As the activity and heat generation of radioactive waste decrease with time, it is advantageous to store high level waste for some decades to facilitate the encapsulation and disposal operations. Longer interim storage might be justified e.g. if a much better disposal method is foreseen to become available later.

Protection against diversion of fissile materials for production of nuclear weapons is accomplished by the safeguards system operated by the IAEA in collaboration with national authorities. In principle the safeguards system covers also disposal of high-level waste including spent fuel, but the surveillance has not yet been established. The safeguards surveillance during the disposal operations will probably be made as that of present nuclear fuel handling facilities. Although the retrieval of fissile material in a sealed repository is difficult, the post closure safeguards aspects should be carefully considered in the implementation of disposal.

B. Radiation protection principles

The proposed Nordic recommendations are in alignment with the ICRP system of radiation protection consisting of the three general principles justification of practice, optimization of protection and individual dose and risk limits. The applied principles presented below clarify the application of the general principles to disposal of HLW.

Applied principle 1: Optimization

The system of waste disposal shall be optimized. In doing so radiation doses and risks must be compared and balanced against many other factors that could influence the optimized solution.

Comments: Despite the difficulties the principle of optimization should be used to guide analysis throughout the processes of site selection, waste conditioning and repository design. Optimization will often include engineering judgements rather than rigorous safety or performance analysis. In particular cases, a decision-aiding methodology, such as multi-attribute analysis, may be helpful for structuring the information and distinguishing between the various alternatives.

Applied principle 2: 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 per 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 per year.

Comments: Because of different diets, living habits and environmental conditions, there is always a "tail" in individual dose or risk distribution. Sometimes this tail may exceed the respective constraint though the average value in the critical group remains low. This is not specific to disposal of waste. The concept of critical group allows the exposure of a few persons with extreme habits and characteristics to much higher dose than the average. Acceptance of the tail in dose or risk distribution is not contrary to the present practices and is consistent with the individual protection principle.

Primarily due to environmental uncertainties it is not well- founded to extend individual dose or risk predictions and comparisons with the respective constraints into the very far future. In general dose assessments beyond about ten thousands years are very uncertain.

Dose assessment in the relative sense can be made for longer time periods assuming hypothetical critical groups. In that case the resulting doses or risks should be interpreted as safety indicators (relative measures of safety), not as predictions of really occurring doses. Such analyses should be extended to time periods until the calculated doses are no longer increasing or the related uncertainties are too high.

Applied principle 3: 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 inflows of the disposed radionuclides into the biosphere, averaged over long time periods, shall be low in comparison with the respective inflows of natural alpha emitters.

Comments: A practicable measure for the total radiological impact is the activity inflow of the disposed radionuclides from geosphere to biosphere, as it is not unreasonably affected by future environmental changes. The activity inflow should be averaged over long time periods, i.e. 10^4 years or more, as it is not possible to determine accurately when releases or their peak values occur.

The activity inflow constraint should be such that

i. the resulting peak individual doses should not be in excess of the dose limit and even in the most extreme cases well below the level of deterministic health effects;

ii. the resulting activity concentrations in primary recipients at the disposal site fall within the range of the typical concentrations of long-lived natural alpha emitters in similar environments;

iii. the activity inflow from all wastes to be disposed of globally is low compared with the respective inflow of long-lived natural alpha emitters;

In the absence of extensive biospheric analyses, it is currently not possible to give definite numerical values for the activity inflow constraint. However, calculations indicate that an appropriate constraint probably would fall within the following ranges:

a. 10 - 100 kBq/a for the long-lived alpha emitters

b. 100 - 1000 kBq/a for the other long-lived nuclides per amount of waste, which is produced when one ton of natural uranium is processed into nuclear fuel and then used in a reactor.

Demonstration of compliance with the activity inflow constraint is more straightforward then with e.g. dose constraints.

C. Assurance principles

A high degree of confidence in the safety of the disposal system is needed before implementation of a disposal concept. The assurance principles below clarify, how the compliance with radiation protection constraints and other design bases should be demonstrated and illustrated.

Assurance principle 1: Safety assessments

Compliance of the overall disposal system with the radiation protection criteria shall be demonstrated by means of safety assessments which are based on qualitative judgement and quantitative results from models that are validated as far as practicable.

Comments: Risk scenarios for which quantitative assessments are impossible, can be interpreted as "rest risks". Their acceptability need not to be deemed against the constraints but still the risks from them should be limited as far as practicable.

Assurance principle 2: *Quality assurance*

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

Assurance principle 3: Multibarrier principle

The long-term safety of waste disposal shall be based on passive multiple barriers so that

a. deficiencies in one of the barriers do not substantially impair the overall performance of the disposal system

b. realistic geologic changes are likely to affect the system of barriers only partly.

D. Technical and geological recommendations

Recommendation 1: Site geology

The site should provide good natural conditions for the containment and isolation of radioactive substances. Thus a good site should

a. have hydrogeological characteristics that provide low groundwater flow within the repository, long groundwater transit time from the repository to the biosphere and favorable dispersal characteristics

b. have geochemical characteristics that contribute to low corrosion rate of the canister material, low dissolution rate of the waste matrix as well as to low solubility and effective retardation of the released radioactive substances

c. be located in a region of low tectonic and seismic activity

d. not be adjacent to such natural resources as are not readily available from other sources

e. be easy to characterize.

Recommendation 2: Repository design

The repository should be located

a. at a sufficient depth to protect the waste packages from external events and processes and render inadvertent human intrusion very unlikely

b. in a host rock formation large enough to accommodate the repository and the buffer zones

The configuration of the repository should be such that

c. the temperature rise due to heat generation from the waste packages remains at an adequately low level

d. the extent of potentially adverse geochemical disturbances due to the emplaced waste is limited

e. the increase of fracturing due to the repository construction or the emplaced waste is limited

f. the emplaced waste remains sub-critical with respect to nuclear fission even in the long term.

Recommendation 3: Backfilling and closure

The backfilling and closure of the repository should contribute favorably to the containment and isolation capability of the disposal system. The backfilling material around the waste packages should

a. protect the waste package from minor rock movements

b. further reduce the mass transfer rate of corroding and dissolving agents and released radioactive substances around the waste packages

c. have a sufficient mechanical and chemical long term stability

The closure of the repository should aim at

d. limiting groundwater flow in the repository

e. disconnecting groundwater flowpaths that might adversely affect the safety of disposal

f. maintaining long term structural stability in the repository

g. preventing inadvertent human intrusion into the repository.

Recommendation 4: Waste package

The waste packages should provide technical barriers which will effectively contain and isolate radioactive substances. Thus the waste packages should:

a. have such mechanical and chemical stability as to provide a substantially complete isolation of radioactive substances for an adequately long period, and thereafter

b. limit the average releases rate of radioactive substances from the repository to a sufficiently low level.

In the selection of material for the waste packages, consideration should be given to their value as attractive targets for future explorations.

FINAL REMARKS

The Nordic criteria for disposal of HLW are generally speaking in alignment with other national and international criteria or proposals of criteria but they are in some parts innovative and the ideas given are taken up and reflected in late international and national publications.

However the Nordic criteria are certainly not complete but constitute an important step forward. They will together with other international criteria constitute a basis for the development of national regulatory activity on the subject.

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