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LONG-TERM SAFETY OF DISPOSAL OF SPENT NUCLEAR FUEL

1. General

This Guide specifies the requirements given in the Government Decision (478/1999) (hereafter called Government Decision) for the safety of disposal of spent nuclear fuel. The Guide addresses disposal into a repository in crystalline bedrock at the depth of several hundreds of meters and covers the long-term safety of disposal. The requirements concerning the operational safety of a disposal facility are given in Guide YVL 8.5.

2. Radiation safety

2.1. General principle

In Sections 5 and 6 of the Government Decision, long-term radiation protection objectives are given for the design and implementation of a disposal facility. In accordance with the optimisation principle included in Section 2 of the Radiation Act and the continuous safety improvement principle included in Section 12 of the Government Decision, all practicable means shall be adopted for further reduction of radiation exposure, although the constraints were met.

2.2. Application of the dose constraints

In accordance with Subsection 3 of Section 5 of the Government Decision, *in an assessment period that is adequately predictable with respect to assessments of human exposure but that shall be extended to at least several thousands of years:*
(1) the annual effective dose to the most exposed members of the public shall remain below 0.1 mSv; and
(2) the average annual effective doses to other members of the public shall remain insignificantly low.

These constraints apply to radiation doses which arise to members of the public as a consequence of expected evolution scenarios and which are reasonably predictable with regard to the changes in the environment. Humans are assumed to be exposed to radioactive substances released from the repository, transported to near-surface groundwater bodies and further to watercourses above ground. At least the following potential exposure pathways shall be considered:

- use of contaminated water as household water;
- use contaminated water for irrigation of plants and for watering animals;
- use of contaminated watercourses and relictions.

Changes in the environment to be considered in applying the dose constraints include at least those arising from land uplift. The climate type as well as the human habits, nutritional needs and metabolism can be assumed to be similar to the current ones.

The constraint for the most exposed individuals, effective dose of 0,1 mSv per year, applies to a self-sustaining family or small village community living in the vicinity of the disposal site, where the highest radiation exposure arises through the pathways discussed above. In the environs of the community, a small lake and a shallow water well is assumed to exist.

In addition, assessment of safety shall address the average effective annual doses to larger groups of people, who are living at a regional lake or at a coastal site and are exposed to the radioactive substances transported into these watercourses. The acceptability of these doses depend on the number of exposed people, but they shall not be more than one hundredth – one tenth of the constraint for the most exposed individuals.

2.3. Application of the activity release constraints

In accordance with Section 5 of the Government Decision, *the average quantities of radioactive substances over long time periods, released from the disposed waste and migrated to the environment, shall remain below the nuclide specific constraints defined by the Radiation and Nuclear Safety Authority. These constraints shall be defined so that:*
(1) at their maximum, the radiation impacts arising from disposal can be comparable to those arising from natural radioactive substances; and
(2) on a large scale, the radiation impacts remain insignificantly low.

The nuclide specific constraints for the activity releases to the environment are as follows:

- 0,03 GBq/a for the long-lived, alpha emitting radium, thorium, protactinium, plutonium, americium and curium isotopes;
- 0,1 GBq/a for the nuclides Se-79, I-129 and Np-237;
- 0,3 GBq/a for the nuclides C-14, Cl-36 and Cs-135 and for the long-lived uranium isotopes;
- 1 GBq/a for Nb-94 and Sn-126;
- 3 GBq/a for the nuclide Tc-99;
- 10 GBq/a for the nuclide Zr-93;
- 30 GBq/a for the nuclide Ni-59;
- 100 GBq/a for the nuclides Pd-107 and Sm-151.

These constraints apply to activity releases which arise from the expected evolution scenarios and which may enter the environment not until after several thousands of years. These activity releases can be averaged over 1000 years at the most. The sum of the ratios between the nuclide specific activity releases and the respective constraints shall be less than one.

2.4. Consideration of unlikely events

In accordance with Section 6 of the Government Decision, *the importance to long-term safety of unlikely disruptive events impairing long-term safety shall be assessed and, whenever practicable, the acceptability of the consequences and expectancies of radiation impacts caused by such events shall be evaluated in relation to the dose and release rate constraints specified in Section 5 of the Government Decision.*

The unlikely disruptive events impairing long-term safety, referred to above, shall include at least:

- boring a deep water well at the disposal site;
- core-drilling hitting a waste canister;
- a substantial rock movement occurring in the environs of the repository.

The importance to safety of any such incidental event shall be assessed and whenever practicable, the resulting annual radiation dose or activity release shall be calculated and multiplied by the estimated probability of its occurence. The expectation value shall be below the radiation dose or activity release constraints referred to in Chapters 2.2. and 2.3. If, however, the resulting individual dose might imply deterministic radiation impacts (dose above 0,5 Sv), the order of magnitude estimate for its annual probability of occurrence shall be 10^{-6} at the most.

2.5. Consideration of protection of other living nature

Disposal of spent fuel shall not affect detrimentally to species of fauna and flora. This shall be demonstrated by assessing the typical radiation exposures of terrestrial and aquatic populations in the disposal site environment, assuming the present kind of living populations. These exposures shall remain clearly below the levels which, on the basis of the best available scientific knowledge, would cause decline in biodiversity or other significant detriment to any living population. Moreover, rare animals and plants as well as domestic animals shall not be exposed detrimentally as individuals.

3. Design principles for disposal

3.1. Way of implementation and scheduling

In accordance with Section 7 of the Government Decision, *the implementation of disposal, as a whole, shall be planned with due regard to safety. The planning shall take account of the decrease of the activity of spent fuel by interim storage and the utilisation of best available technology and scientific knowledge. However, the implementation of disposal shall not be unnecessarily delayed.*

Disposal shall be planned so that no monitoring of the disposal site is required for ensuring long-term safety and so that retrievability of the waste canisters is maintained to provide for such development of technology that makes it a preferred option.

Subsequent to the selection of a disposal site, implementation of spent fuel disposal includes the following phases:

- construction and operation of an underground research facility and other necessary research, development and planning work;
- construction of the disposal facility (encapsulation facility, repository and auxiliary facilities);
- encapsulation of spent fuel bundles and transfer of waste canisters into their deposition positions;
- closure of emplacement rooms and other underground rooms;
- post-closure monitoring, if required.

These phases, which can be partly parallel, shall be scheduled and implemented with due regard to long-term safety. In doing so, the following aspects shall be considered:

- reduction of the activity and heat generation in waste prior to disposal;
- introduction of the best available technique or a technique that is becoming available;
- acquisition of adequate experimental knowledge of the disposal site and other factors affecting long-term safety;
- potential surveillance actions related to ensuring the long-term safety or to non-proliferation of nuclear materials;
- need for preserving the retrievability of the disposed waste canisters;
- aim of preserving the natural features of the host rock and other favourable conditions in the repository;
- aim of limiting the hazards and other burdens to future generations due to long-term storage of waste.

In the post-closure phase, retrieval of the waste canisters from the repository shall be feasible during the period in which the engineered barriers are required to provide practically complete containment for the disposed radioactive substances. The disposal facility shall be designed so that retrieval of waste canisters, if needed, is feasible with the technology available at the time of disposal and with reasonable resources. Facilitation of retrievability or potential post-closure surveillance actions shall not impair the long-term safety.

On the basis of primary records and verification measurements, adequate inventory data of the nuclear materials and nuclear wastes to be disposed of, shall be obtained during the operational period of the disposal facility for long-term deposition. The disposal facility shall be designed so that, in the post-closure period, it is feasible to implement arrangements for discovering and precluding actions on the repository which would jeopardise the long-term safety or involve breach of the treaties concerning nuclear materials' security.

Implementation of disposal and related research, development and safety assesement work shall be based on an appropriate quality management system that shall be extended to all organisations contributing significantly to the long-term safety.

3.2. Barriers

In accordance with Section 8 of the Government Decision, *the long-term safety of disposal shall be based on redundant barriers so that deficiency in one of the barriers or a predictable geological change does not jeopardise the long-term safety. The barriers shall effectively hinder the release of disposed radioactive substances into the host rock for several thousands of years.*

Engineered barriers may consist of:
- hermetic, corrosion resistant and mechanically strong container, where the fuel bundles are enclosed;
- uranium matrix of low solubility, where most of the radioactive substances are incorporated;
- the chemical environment of waste canisters, which limits the dissolution and migration of radioactive substances;
- the backfilling material (the buffer) around waste canisters, which provides containment and yields minor rock movements;
- the backfilling materials and sealing structures, which limit transport of radioactive substances through excavated rooms.

Natural barriers may consist of:
- the intact rock around the disposal tunnels, which limits groundwater flow around waste canisters;
- the host rock where low groundwater flow, reducing and even otherwise favourable groundwater chemistry and retardation of dissolved substances in rock limit the mobility of radionuclides;
- the containment provided by the host rock against natural phenomena and human actions.

Targets for the long-term performance of each barrier, shall be determined based on best available experimental knowledge and expert judgement. The performance of a barrier may diverge from the respective target value due to rare incidental deviations such as manufacturing or installation failures of engineered barriers, random variations in the characteristics of the natural barriers or erroneous determination of the characteristics. However, the performance targets for the system of barriers as a whole shall be set so that the safety requirements are met notwithstanding the deviations referred to above.

The determination of the performance targets for the barriers shall be based on an assumption that, due to some unpredicted phenomenon, the performance of a single barrier as a whole may be significantly lower than the respective target value. The safety requirements shall be met even in such case.

The determination of the performance of barriers shall take account of changes and events that may occur in various assessment periods. The characteristics of the host rock can be assumed to remain in their present state up to an assessment period of sev eral thousands of years. However, the effects of predictable processes, such as land uplift and disturbances due to the excavations and the disposed waste, shall be taken into account. The performance targets for the engineered barriers shall be set so that there will be no releases of radioactive substances into the host rock during the assessment period of several thousands of years.

3.3. Disposal site and the repository

In accordance with Section 9 of the Government Decision, *the geological characteristics of the disposal site shall, as a whole, be favourable for the isolation of the disposed radioactive substances from the environment. An area having a feature that is substantially adverse to long-term safety shall not be selected as the disposal site.*

In accordance with Section 10 of the Government Decision, *the repository shall be located at a sufficient depth in order to mitigate the impacts of above-ground events, actions and environmental changes on the long-term safety and to render inadvertent human intrusion to the repository very difficult.*

The characteristics of the host rock shall be such that it adequately acts as a natural barrier, as specified in Chapter 3.2. Besides that, the characteristics of the host rock shall be favourable with respect to the long-term performance of engineered barriers. Such conditions in the host rock as are of importance to long-term safety, shall be stable or predictable up to at least several thousands of years. The range of geological changes which occur thereafter due to e.g. the large scale climate changes, shall be estimable and be considered in the determination of the performance targets for the barriers.

Factors indicating unsuitability of a disposal site include:
- proximity of exploitable natural resources;
- abnormally high rock stresses;
- predictable anomalously high seismic or tectonic activity;
- exceptionally adverse groundwater characteristics, such as lack of reducing buffering capacity and high concentrations of substances which might substantially impair the performance of barriers.

The location of the repository shall be favourable with regard to the groundwater flow regime at the disposal site.

The disposal depth shall be selected with due regard to long-term safety, taking into account at least:
- the geological structures and lithological properties of the host rock;
- the trends in rock stress, temperature and groundwater flow rate with depth;

To ensure that the effects of above ground natural phenomena, such as glaciation, and human activities will remain low enough, the repository shall be located at the depth of several hundreds of meters.

The structures of the host rock of importance to groundwater flow, rock movements or other factors relevant to long-term safety, shall be defined and classified. The waste canisters shall be emplaced in the repository so that adequate distance remains to such major structures of the host rock which might constitute fast transport pathways for the disposed radioactive substances or otherwise impair the performance of barriers.

The methods adopted for the construction, operation and closure of the repository shall be selected with due regard to preserving the natural barrier characteristics of the host rock. The transport into the repository of substances which are adverse to long-term safety, such as organic or oxidising substances, shall be limited to the minimum.

4. Demonstration of compliance with the safety requirements

4.1. General approach

In accordance with Section 28 of the Government Decision, *compliance with the long-term radiation protection objectives as well as the suitability of the disposal concept and site shall be justified by means of a safety analysis that addresses both the expected evolutions and unlikely disruptive events impairing long-term safety*.

A safety analysis shall include:
- description of the disposal system (waste canister, backfilling materials and sealing structures, excavated rooms, characteristics of host rock, groundwater and the disposal site) and definition of the barriers;
- analysis of the potential future evolutions of the disposal system (scenarios analysis);
- definition of the performance targets for the barriers;
- functional description of the disposal system by means of conceptual and mathematical modelling and the determination of the input data needed in these models;
- analysis of the activity releases and resulting doses from radionuclides which are released from the waste, penetrate the barriers and enter to the biosphere;
- whenever practicable, estimation of the probabilities of activity releases and radiation doses arising from unlikely disruptive events impairing long-term safety;
- uncertainty and sensitivity analyses and complementary discussions on the significance of such phenomena and events which cannot be assessed quantitatively;
- comparison of the outcome of analyses with the safety requirements;
- documentation of the safety analysis.

The various phases of the safety analysis shall be carefully documented. Documentation shall target to:
- transparency, so that the approaches, methods, results and the coupling to the entirety in each part of the analysis can easily be discovered;
- tracebility, so that justifications for the adopted assumptions, input data and models can easily by found in the safety assessment report or its reference reports.

A safety analysis shall be included in the decision-in-principle application, preliminary safety analysis report, final safety analysis report and final closure plan. Furthermore, the safety analysis shall be updated in case that any new information has emerged which might crucially affect the outcome of the analysis in relation to the safety requirements.

4.2. Analysis of scenarios

A scenario analysis shall cover both the expected evolutions of the disposal system and unlikely disruptive events affecting long-term safety. The scenarios shall be composed systematically from features, events and processes, which are potentially significant to long-term safety and may arise from:

- mechanical, thermal, hydrological and chemical processes and interactions occurring inside the disposal system;
- external events and processes, such as climate changes, geological processes and human actions.

The base scenario shall assume the performance targets defined for each barrier, taking account of the incidental deviations from the target values. The influence of the declined overall performance of a single barrier or, in case of coupling between barriers, the combined effect of the declined performance of more than one barriers, shall be analysed by means of variant scenarios. Disturbance scenarios shall be defined for the analysis of unlikely disruptive events affecting long-term safety.

4.3. Modelling and input data

In accordance with Section 29 of the Government Decision, *the calculational methods adopted for the safety analysis shall be selected on the basis that the results of the analysis, with high degree of confidence, overestimate the radiation exposure or radioactive release likely to occur.*

In order to assess the release and transport of disposed radioactive substances, conceptual models shall first be drawn up to describe the physical phenomena and processes affecting the performance of each barrier. Besides the modelling of release and transports processes, models are needed to describe the circumstances affecting the performance of barriers. From the conceptual models, the respective calculational models are derived, normally with simplifications. Simplification of the models as well as the determination of input data for them shall be based on the principle that the performance of any barrier will not be overestimated but neither overly underestimated.

The modelling and determination of input data shall be based on the best available experimental knowledge and expert judgement obtained through laboratory experiments, geological investigations and evidence from natural analogues. The models and input data shall be appropriate to the scenario, assessment period and disposal system of interest. The various models and input data shall be mutually consistent, apart from cases where just the simplifications in modelling or the aim of avoiding the overestimation of the performance of barriers implies apparent inconsistency.

4.4. Complementary considerations

The importance to safety of such scenarios that cannot reasonably be assessed by means of quantitative analyses, shall be examined by means of complementary considerations. They may include e.g. bounding analyses by simplified methods, comparisons with natural analogues or observations of the geological history of the disposal site. The significance of such considerations grows as the assessment period of interest increases, and the judgement of safety beyond one million years can mainly be based on the complementary considerations.

Complementary considerations shall also be applied parallel to the actual safety analysis in order to enhance the confidence in results of the whole analysis or a part of it.

TIME PERIODS

OPERATIONAL PERIOD

- Some tens of years
- Compliance verification feasible

REASONABLY PREDICTABLE FUTURE

- Conservative estimates of human exposure feasible
- Up to several thousands of years

ENVIRONMENTALLY UNPREDICTABLE FUTURE

- From the onset of next glaciation
- Estimation of human exposure meaningless

RADIATION PROTECTION CRITERIA
Reasonably predictable future

GOVERNMENT DECISION OF 1999

- Highest individual doses < 0,1 mSv/a
- Insignificant average doses to larger population groups

STUK GUIDE OF 2001

- Critical group: a self-sustaining community
- Scenarios to be considered
    - use of contaminated water as household water
    - use contaminated water for irrigation of plants and for watering animals
    - use of contaminated watercourses and relictions
- Present type of climate and lifestyles
- Average dose to larger populations 1 - 10 micro Sv/a at most

RADIATION PROTECTION CRITERIA
Very far future

GOVERNMENT DECISION OF 1999

- Maximum impacts comparable to those arising from natural radionuclides
- Insignificant large-scale impacts
- STUK defines activity release constraints

STUK GUIDE OF 2001

Activity release rate constraints:

- 0,03 GBq/a for radium, thorium, protactinium, plutonium, americium and curium isotopes
- 0,1 GBq/a for Se-79, I-129 and Np-237
- 0,3 GBq/a for C-14, Cl-36, Cs-135 and for U-isotopes
- 1 GBq/a for Nb-94 and Sn-126
- 3 GBq/a for Tc-99
- 10 GBq/a for Zr-93
- 30 GBq/a for Ni-59
- 100 GBq/a for Pd-107 and Sm-151

Averiging over 1000 a at the most

GEO-BIO FLUX CONSTRAINTS
Consideration of local impacts

ASSUMED SCENARIOS:

- Sallow well; household water, garden irrigation and domestic animal watering
- Small lake; fishing, irrigation and grazing at shore
- Sediment of a drained lake; agriculture and soil fertilising

WELL DILUTION FACTOR ISSUE:

- The Finnish PA TILA-99: 100 000 m^3/a
- The Swedish PA SITE-94 : 10 000 m^3/a
- The Swedish PA SR-97: 2 600 m^3/a

A SITE SPECIFIC GW FLOW ANALYSIS:

- Range 29 000 - 460 000 m^3/a
- Adopted value: 90 000 m^3/a

DOSE CONVERSION FACTORS

Nuclide	Dose conversion factor (Sv/Bq)	Critical scenarios/pathways
C-14	5 E-13	Lake/fish and sediment/crop
Cl-36	2 E-14	Well/drinking water and lake/fish
Ni-59	4 E-15	Sediment/crop
Se-79	1 E-13	Lake/fish and well/vegetables
Zr-93	1 E-14	Well/drinking water
Nb-94	6 E-14	Well/external radiation
Tc-99	3 E-14	Sediment/crop
Pd-107	5 E-16	Well/drinking water and vegetables
Sn-126	1 E-13	Lake/fish and well/drinking water
I-129	2 E-12	Well/drinking water and vegetables
Cs-135	3 E-13	Lake/fish and sediment/crop
Ra-226	3 E-12	Well/drinking water and vegetables
Th-229	8 E-12	Well, inhalation and drinking water
Pa-231	1 E-11	Well/inhalation and drinking water
U-238	4 E-13	Well/drinking water
Np-237	1 E-12	Well/drinking water
Pu-239	4 E-12	Well/inhalation and drinking water
Am-243	3 E-12	Well/drinking water and inhalation
Cm-245	3 E-12	Well/drinking water and inhalation

Geo-bio flux constraint = 0,1 mSv/a / DCF

GEO-BIO FLUX CONSTRAINTS

Consideration of large-scale impacts

AVERAGE DOSE FROM SEAFISH

<< 1 microSv/a

NATURAL RADIONUCLIDE FLUXES VIA LOCAL AND REGIONAL RIVERS

- **U, Ra, Th: 10 - 100 times the constraints**
- **C-14: 1-10 times the constraints**

RELEASES FROM NORM PRACTICES

- **U, Th, Ra: from a single source, more than 10 times the constraints**

GEO-BIO FLUX vs DOSE
Pros and cons as safety indicator

GEO-BIO FLUX	DOSE
• Burden on rulemaker	• Burden on implementer
• Focus on overall containment capability	• Focus on peak releases and doses
• Nuclide specific constraints	• Incorporates all nuclides
• Benchmarking not established	• Established acceptability levels