SKI Report 01:4
SSI-report 2001:03

SKI and SSI's Joint Review of SKB's Safety Assessment Report, SR 97

Review Report

May 2001

Statens strålskyddsinstitut
Swedish Radiation Protection Institute

SKi

ISSN 1104-1374
ISSN 0282-4434
ISRN SKI-R–01/4–SE

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Foreword

The Swedish Nuclear Power Inspectorate's (SKI) and the Swedish Radiation Protection Institute's (SSI) joint regulatory review of the Swedish Nuclear Fuel and Waste Management Co's (SKB) safety assessment, SR 97 ("Deep Repository for Spent Nuclear Fuel, SR 97 – Post-closure Safety") is presented in this report. The regulatory review report is primarily aimed at SKB and other experts within the nuclear waste area. The authorities have also published a summary aimed at the municipalities involved in SKB's feasibility studies and the general public.

This regulatory review was performed by a project team comprising representatives from the Office of Nuclear Waste Management Safety and the Office of Waste and Environment at SKI and SSI, respectively. The following individuals were responsible for writing the report (area of responsibility and main area of expertise specified in brackets):

SKI:

Björn Dverstorp	(Project Manager and Editor; hydrology, safety assessment methodology)
Fritz Kautsky	(climate, earthquakes and tectonics)
Christina Lilja	(canister, corrosion and heat generation)
Bo Strömberg	(spent fuel, geochemistry and radionuclide transport)
Öivind Toverud	(geology and buffer)
Magnus Westerlind	(regulations and the decision-making process)
Stig Wingefors	(regulations and system description)

SSI:

Mikael Jensen	(SSI's Project Manager; risk criteria, human impact)
Leif Moberg	(biosphere processes and environmental protection)
Anders Wiebert	(scenario and risk analysis)

In addition to the above, several experts at each regulatory authority were consulted by the project team, including Carl-Magnus Larsson, Rodolfo Avila, Synnöve Sundell-Bergman and Åsa Wiklund from SSI and Benny Sundström from SKI.

Stockholm, November 7, 2000

Björn Dverstorp	Mikael Jensen
Office of Nuclear Waste Safety	Office of Waste and Environment
Swedish Nuclear Power Inspectorate	Swedish Radiation Protection Institute

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1 SKI and SSI's Review

1.1 Background

Safety assessment plays an important role as a control instrument for research and development and as a basis for decision-making for the construction, ownership and operation of nuclear facilities. Since 1990, SKI has consistently emphasized the importance of safety assessment in connection with all of the reviews of SKB's RD&D Programme (SKI 1993, 1995, 1996a, 1999a, 1999b). SKI's review statements and the government decisions on the 1995 and 1998 RD&D programmes are of particular importance for SKB's current safety assessment, SR 97.

In its review statement (SKI, 1996a) on RD&D Programme 95, SKI stated that SKB had made considerable progress on the safety assessment and that it was time to apply and evaluate newly developed methodology and methods. In SKI's opinion, and in the opinion of a number of reviewing bodies, there were a number of reasons why a safety assessment should be reported and reviewed before SKB pursued activities which involve stronger commitments to KBS-3. SKI therefore proposed that the Government, with the support of § 12 of the Act (1984:3) on Nuclear Activities, should *"impose the condition that before SKB initiates site investigations, SKB should present an in-depth and comprehensive safety assessment of SKB's proposed main system alternative as well as commission and present an independent peer review of the safety assessment by national and international experts"*.

On December 19, 1996, the Government made a decision on RD&D Programme 95, largely along the lines of SKI's proposal. The decision stipulates that an assessment of the long-term safety of the repository should be conducted as a condition for SKB's further work. The Government does not state a specific time when the assessment should be completed, but in the reasons for its decision, the Government states that *"in the Government's opinion, an assessment of the long-term safety of the repository should be performed before an application for a licence to construct the planned encapsulation plant is submitted to the regulatory authorities and before site investigations are initiated at one or more sites"*.

The importance of the safety assessment, in general, and as part of the basis for decision-making prior to site investigations is discussed again by SKI in connection with its review of SKB's RD&D Programme 98. In its review (SKI, 1999a), SKI states that one of the purposes of SR 97 is to show that KBS-3 would have good prospects of meeting long-term safety and radiation protection requirements. It was possible to specify this purpose since SSI had promulgated regulations for the final disposal of spent nuclear fuel and nuclear waste (SSI, 1999), and SKI had drafted and submitted for review premises upon which regulations for safety for the final disposal of nuclear waste would be based (SKI dnr. 5.8-970478, March 24, 1997, *SKI's Premises for Regulations and General Recommendations for the Final Disposal of Spent Nuclear Fuel etc.*). During 1999, draft regulations were written and submitted for an initial review (SKI dnr. 5.1-990760, June 3, 1999, *Draft Regulations for Safety in connection with Final Disposal*). The authorities' regulations have therefore been promulgated at a relatively late stage of SKB's work on SR 97, which has been taken into account in this review, see Chapters 2 and 3 for detailed comments.

SKI proposed that the Government, in its decision on RD&D Programme 98 should repeat the stipulation that SKB should conduct a safety assessment. However, SKB concluded its assessment and submitted the report to SKI for review in December 1999, namely, before the Government had made a decision on RD&D Programme 98. Therefore, the Government has not repeated the stipulation, but merely states that *"the Government has also been informed that the Swedish Nuclear Power Inspectorate and the Swedish Radiation Protection Institute have started their joint review of SR 97 and that they have also initiated an independent international peer review of the safety assessment"*.

1.2 Purposes

Based on the reviews and government decisions on RD&D Programme 95 and 98, the purposes of SR 97 can be defined as follows:

- to show that KBS-3 would have good prospects of meeting long-term safety and radiation protection requirements and to demonstrate the feasibility of finding a site in Sweden that meets the requirements
- to demonstrate safety assessment methodology
- to provide data for measurement programmes for geoscientific site investigations and to evaluate the measurement results
- to provide data for the specification of requirements with respect to the canister and other barrier functions
- to contribute to specifying the factors that serve as a basis for the selection of sites for site investigations.

The aim of the regulatory review is, in turn, to evaluate the extent to which SR 97 fulfils the purposes presented above. This review primarily addresses the purposes in bullet points 1 and 2, although 3 and 4 are also dealt with. Based on the SR 97 main report and background reports, it is not possible for the authorities to evaluate the way in which SKB uses the results from SR 97 to specify site selection criteria. Such an evaluation can only be made when additional material has been submitted by SKB. This material will be included in the supplement to RD&D Programme 98 that SKB plans to submit in December 2000 as a result of the Government's decision on RD&D Programme 98.

In order to contribute to the breadth and depth of the regulatory review, since its review of RD&D Programme 95 SKI has advocated and planned an international peer review of SR 97. In spring 1999, the OECD's Nuclear Energy Agency (NEA) appointed an International Review Team to conduct an international peer review of SR 97. Experts were selected by NEA on the basis of certain criteria established by SKI (SKI, 1999c). These criteria included the requirement that experts who had worked on major projects on behalf of SKB over the past six years should be excluded from the team and that there should be a reasonable balance between representatives from the nuclear industry and from the regulatory authorities. The purposes of the peer review were essentially the same as those presented above.

1.3 Implementation of the Review

It became clear at an early stage that a close co-operation between SKI and SSI was necessary and desirable for the review of SR 97. In 1999, the authorities agreed to conduct the review in the form of a joint project which would result in a joint review report.

As stated above, an International Review Team (IRT), appointed by NEA, conducted a peer review of SR 97, on behalf of SKI. The IRT started work in December 1999, immediately after SKB had submitted SR 97 to SKI. The review was completed in spring 2000 and the findings were reported at a seminar in Stockholm on May 31, 2000. This review report takes into account the findings of the IRT. The IRT's findings have also been published in a separate report (SKI, 2000a).

The regulatory authorities started their review in December 1999. However, certain preparations had been made during autumn. In February 2000, SKI informed (dnr. 5.8-991436, February 7, 2000) the reviewing bodies of RD&D Programme 98 about the review of SR 97. SKI explained that, in connection with the review of the supplement that the Government requested SKB to submit, the reviewing bodies would also be given the opportunity to comment upon SR 97, in winter/spring 2000. A total of twelve statements of opinion were submitted by reviewing bodies (SKI, 2000b).

In addition, SKI requested The National Council for Nuclear Waste (KASAM) to evaluate SR 97 and KASAM's statement of opinion was submitted to SKI in the beginning of May 2000.

To enhance the depth of the review, SKI commissioned about 15 consultants to evaluate different parts of SR 97 (SKI, 2000c). On several occasions, the consultants had conducted work for SKI and are therefore well acquainted with SKB's programme. SSI also consulted international experts on biosphere and radiation protection-related issues concerning SR 97.

Therefore, in summary, this regulatory review comprises the opinions of the regulatory authorities which have taken into account the following:

- findings of the NEA's International Review Team
- KASAM's opinion
- opinions of the reviewing bodies
- consultants' findings.

In total, just over thirty Swedish and international experts contributed to the regulatory review.

1.4 Review Report

The regulatory review report consists of a general part containing conclusions and two appendices with detailed comments upon which the conclusions are based.

Opinions from KASAM and other reviewing bodies are reported under separate headings in the review report. On the other hand, the findings of the NEA's International Review Team and of the consultants are presented along with the opinion of the authorities, since these reviews were directly commissioned by the authorities.

SKI and SSI's premises for the review of SR 97 – largely based on the requirements and regulations of each authority – are presented in Chapter 2 of the review report. Furthermore, a discussion is presented of the extent to which certain requirements are appropriate to the current situation and of those requirements that will become meaningful at later stages, such as in connection with an application to construct, own and operate a repository.

Several of the authorities' requirements and regulations are of a general nature. This means that it is up to SKB to interpret them. The authorities' evaluation of SKB's interpretation is presented in Chapter 3. In addition, SKB's own overall safety strategy and the extent to which it agrees with the authorities' view is evaluated.

A central component of the regulatory review has been to evaluate SKB's methodology for safety assessment structure, implementation and reporting and to evaluate how this methodology has been applied in SR 97. Therefore, Chapter 4 deals with SKB's methodology for the identification and selection of scenarios, risk assessment and probabilistic calculations, how SKB has selected data and models, how uncertainties in data, models and scenarios have been analyzed etc.

Finally, SKI and SSI's overall evaluation of SR 97 is presented in Chapter 5 as well as the extent to which SR 97 fulfils its intended purposes.

More detailed comments on processes and initial states for engineered barriers, the geosphere and biosphere are presented in Appendix 1. The five scenarios for repository evolution that SKB has analyzed are reviewed in order in Appendix 2. This does not mean that the authorities consider that SKB's scenario selection is complete or correct in all respects. The purpose of Appendix 2 is to make it easy for the reader to locate the review of the scenarios analyzed by SKB.

In its decision on RD&D Programme 98, the Government stated that *"the Government places considerable importance on the presentation of the safety assessment and review findings in a way that makes them comprehensible, even to non-experts."* In addition to the opinions presented in this review report, the authorities have also prepared an easy-to-read summary (SKI, 2000d).

2 Premises for the Regulatory Review

2.1 Background

This section provides an overview of the general premises for the regulatory review of safety assessments, including of the various types of requirements that can be made on a safety assessment in different contexts.

As the competent regulatory authorities for the Swedish nuclear waste programme, SKI and SSI must supervise work in this area in accordance with the Act on Nuclear Activities and the Radiation Protection Act. A short description of the implications of this supervision and the role of the safety assessment is provided at the end of this section along with information concerning the relevant acts and ordinances.

2.1.1 Premises for the Review of Safety Assessments

Safety Assessments at Different Stages of a Final Disposal Programme

A complete safety report must be prepared no later than before a decision is made to construct a facility. In addition to this more obvious role, a safety assessment is also a tool in the early stages of a final disposal programme. In the research and development work on final disposal, one of the few available tools for guiding and controlling activities with respect to long-term safety and radiation protection is the safety assessment. The use of the safety assessment for this purpose can occur on different scales – from rough estimates regarding specific details to major co-ordinated (integrated) analyses.

In general, the premises for facilities in operation are different from those for facilities that are still at the planning stage or those that have not been taken into operation. The premises for the planned Swedish nuclear waste programme have, so far, been developed in the form of government decisions as a result of regulatory reviews of SKB's programme. An obvious premise for the regulatory control of the industry's programme is that as the plans become more detailed and as the deadlines for the siting decision draw closer, the requirements should increase that safety-related issues should be shown to be resolved or to be resolvable. This applies to the treatment of uncertainties and gaps in knowledge as well as to showing how required barrier properties, such as in a repository, can be realized. The safety assessment is an instrument for evaluating how much progress a programme has made in these respects and SR 97 is an example of this.

Another important role of the safety assessment is that of providing a basis for deriving and allocating safety functions in the barrier system. Therefore, the assessment should be used to, if possible, determine functional requirements with respect to the various parts of the barrier system, such as the permeability of the clay buffer or the canister lifetime. Requirements with respect to material properties and barrier manufacture can then be derived at a later stage from these function requirements. In turn, it must then be possible to derive requirements on the tests and control methods that are to be used to verify these properties. An important role for the complete safety report for a repository is to link the requirements on these different levels in a clear and traceable manner. A special case in this respect is deriving requirements on the testing and control methods that shall be used to investigate and verify the properties of the rock as a barrier. These properties should be determined with a reasonable degree of accuracy prior to selecting a repository site. Therefore, a safety assessment showing how the proposed investigation methods meet requirements that can be derived from the more general requirements on the repository should be prepared prior to the site investigations. This was also one of the main purposes of SR 97.

Basis for the Regulatory Review at Different Stages

The basis for the regulatory review of safety assessments may differ depending on the stage of the final disposal programme.

In the early stages of a programme, the safety assessment does not have to provide a detailed investigation of all of the issues relating to the barriers and their performance. The most important aspect is to show the robustness of the principles for the repository design and, in various ways, show that the system components are feasible. Furthermore, at such a stage, no requirements have to be made on data from a complete site investigation or that the repository should be located at a particular site. However, it is always important that the safety assessment method should comply with the overall regulatory requirements and that it should be possible to develop the method to comply with the requirements in connection with future licence applications. This does not only apply to the assessment of the barrier system as such, but also to the assessment of the environmental impact, that is, the migration of radionuclides into the biosphere and the impact of ionizing radiation on human health and on the environment.

A basic requirement that is relevant to all stages is that no unresolved issue should be found to be so serious as to make it impossible to construct a repository that complies with the overall safety and radiation protection requirements. In turn, this requires that the safety assessment should be so complete that this conclusion can be drawn on the basis of the available knowledge. The safety assessment should be both comprehensive and show that no such unresolved issue exists no later than by the time an application is submitted for permission to construct a repository. The evaluation of the degree of completeness of the safety assessment is actually the most important aspect. A safety assessment that is complete should, in principle, unambiguously show the extent to which the overall requirements on safety and radiation protection have been met without the authorities, in the course of their review, having to furnish additional knowledge or develop and apply new review methodology.

2.1.2 International Rules and Guidelines

Over the past 10-15 years, an international consensus has emerged concerning the basic ethical principles for the management and final disposal of spent nuclear waste and spent nuclear fuel (such as IAEA, 1995 and NEA, 1995a). The principles of the international convention of radioactive waste management (i.e., Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management) are based on this consensus. The Convention – the preparation of which was co-ordinated by the IAEA – was ratified by Sweden in 1999 and is expected to enter into force in 2001. The provisions of the Convention include requirements on legislation, regulatory structure and ethical requirements that undue burdens must not be placed on future generations.

The principles that are of particular interest from the standpoint of the long-term safety of the repository include:

- protection of human health
- protection of the environment
- protection over national boundaries
- protection of future generations
- consideration of all stages in the system for the management of radioactive waste
- safety in connection with facility operation

The International Commission on Radiation Protection (ICRP) has with its recommendations been a leading international agency within the radiation protection field for most of the 20th century. The special problems relating to waste, which lead to consequences far into the future, have recently been dealt with by the ICRP in Publication 81. Although SSI's regulations, SSIFS 1998:1, were promulgated before the ICRP published these recommendations, they agree with the ICRP's recommendations.

In addition to rules and recommendations formulated by international organizations, a number of national regulations exist concerning the long-term safety for final disposal and requirements regarding safety assessments. These include the French Règles fondamentales de surêté (DSIN, 1992), guidelines from the Swiss nuclear safety authority, HSK (HSK, 1993) and guidelines published by the Environment Agency in England (EA, 1997) and by the Radiation and Nuclear Safety Authority in Finland (STUK), based on the decisions made by the Finnish Minister (STUK, 1999). Even if there are considerable differences in the structure as a result of differences in legislation and time schedules, these national regulations are essentially in close agreement with those promulgated by the Swedish authorities. Over the past 10 years or so, the Swedish authorities have also been working in close co-operation with HSK (SKI, 1990) and with the Nordic radiation protection and safety authorities (Nordic authorities, 1993). The Swedish authorities are involved, on a continuous basis, in the international work, mainly conducted within NEA and the IAEA, but also within international environmental conventions and the EU.

In the USA, the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC) have presented proposals for regulations for the planned repository in Yucca Mountain, Nevada (EPA, 1999; NRC, 1999). Unlike the Swedish regulations, these are very detailed in terms of scenarios for repository evolution and exposure pathways. This is possible since the regulations are site-specific. The intention is also to avoid lengthy discussions concerning future scenarios.

Regulatory Supervision
As the competent regulatory authorities for the Swedish nuclear waste programme, SKI and SSI must supervise the programme, under the Act on Nuclear Activities and the Radiation Protection Act. In practice, this supervision is conducted through the inspection and evaluation of activities at the different nuclear facilities. The aim of the supervision is to determine whether the legal requirements on the activities are fulfilled and to decide upon measures when necessary. The requirements on the activities are based on the provisions in these acts and ordinances, namely, in the form of stipulations and regulations promulgated by the Government and authorities in connection with the licensing of a particular activity or facility. SKI and SSI also promulgate general regulations in different areas. How the requirements are met in each individual case must be established in the safety report for the facility. The safety assessment is part of the safety report, which mainly consists of a detailed facility description. The safety report is the most important basis for the regulatory review of a facility.

Acts and Ordinances
§ 13 of the Radiation Protection Act (1988:220) stipulates that anyone conducting activities involving radiation is responsible for the management of the waste generated by the activity. The Radiation Protection Ordinance (1988:293) authorizes SSI to supervise such activities in accordance with the Radiation Protection Act.

Under §§ 7 and 8 of the Radiation Protection Ordinance, SSI maypromulgate the regulations that are required for the protection against or control of radiation and for the management of radioactive waste. If a licence is granted to conduct activities under the Act on Nuclear Activities, SSI promulgates the specific radiation protection stipulations that can be required for the activity.

The overall requirements on *safety* in connection with final disposal are provided for in the Act (1984:3) on Nuclear Activities. As a basic provision for nuclear activities, § 4 of the Act on Nuclear Activities stipulates that safety must be maintained through the measures adopted that are required to prevent malfunctions or any other incorrect functioning of equipment, errors or other incidents that can cause a radiological accident. The purpose of the legislation is to ensure that these provisions should also apply to final disposal after repository closure in the sense that the dispersion of radioactive substances over and above levels that are tolerable (from a radiological standpoint) are contained in the concept of "radiological accident". § 10 also stipulates that the holder of a licence to conduct nuclear activities is to be responsible for ensuring that the necessary measures are adopted to handle and finally dispose of nuclear waste generated by the activity or fissile materials generated by the activity that are not re-used.

The Ordinance (1984:14) on Nuclear Activities gives SKI the authority to promulgate any additional stipulations required with respect to safety. SKI is also authorized to promulgate regulations for measures under § 4 of the Act on Nuclear Activities, as described above.

2.2 Radiation Protection Requirements

2.2.1 Overview

SSI's regulations (SSI, 1999) concerning the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste entered into force on February 1, 1999. The regulations do not only apply to the time after repository closure, but also to other steps for waste management that are undertaken prior to final disposal (treatment, interim storage, transport). Several regulations apply to radiation protection for personnel, radioactive releases, documentation etc. during the operating period. It is not necessary to comment upon these regulations here.

2.2.2 Basic Radiation Protection Requirements

"Human health and the environment shall be protected from harmful effects of ionizing radiation during the time when the various stages of the final management of spent nuclear fuel or nuclear waste are being implemented as well as in the future. The final management may not cause impacts on human health and the environment outside Sweden's borders that are more severe than those accepted inside Sweden". (§ 3)

The regulations also contain requirements on optimization, namely that the number of individuals exposed to radiation and the probability of receiving a radiation dose must be limited as far as reasonably achievable. This requirement applies to all operational stages of waste management, such as encapsulation, transport to and within the repository. On the other hand, no requirements are made that doses in an extremely remote future should be balanced against the repository design and construction. (§ 4)

2.2.3 Requirements on Design and Construction

Best Available Technique

SSI requires that a repository should be designed and constructed taking into account the principle of the "best available technique" (BAT). The best available technique refers to the construction, operation, decommissioning, dismantling etc. of a facility. The barrier system for the chosen concept must be constructed using the best technique that is available at the time at a reasonable cost, including the technical-scientific basis for the assessment of the barrier performance and protective capability.

Making Access Easier or Making Intrusion Difficult

A repository must primarily be designed taking into account its capability of protecting the environment from ionizing radiation generated by the deposited waste. Measures adopted in order to facilitate retrieval of the waste or to make intrusion into the repository difficult could be in conflict with this basic principle. Consequently, the effects of such measures on the protective capability must be described (§ 8).

A description of how the protective capability is affected in connection with intrusion into the repository is necessary in order to provide a comprehensive background as a basis for decision-making. For such a scenario to occur, knowledge of the repository would have to be eventually lost and human activities in a remote future would have to unintentionally affect the repository's capability to retain its radioactive inventory or to retard the transport of the radioactive substances into the biosphere. The protective capability of the repository after intrusion must therefore be described, with respect to the long-term consequences (§ 9).

2.2.4 Protection of Human Health

In its radiation protection requirements, SSI has applied the concept of risk as a measure of the requirements that are made on the protection of human health. Risk includes the probability of receiving a radiation dose and the probability of this dose causing harmful effects. “Harmful effects” refers to cancer and genetic damage. The requirement is formulated as follows:

“A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk”. (§ 5)

If the risk is estimated on the basis of the analysis of a number of scenarios, the total risk to an affected group may consist of contributions from several scenarios.

To assess the probability, a holistic description is required, where the scenarios can be identified in mutually exclusive components that together cover all outcomes.

For each calculation case, the description should provide information on the dose distribution, its breadth and other conditions that are important for judging compliance with goals for health and environmental protection resulting from the biosphere scenarios selected by SKB. If SKB decides to make comparisons based on the individual within the group with a high (the highest) dose commitment, the conservatism must be evident through the description of the assumptions used.

2.2.5 Environmental Protection

The wording of SSI’s environmental protection requirements is more general:

“The final management of spent nuclear fuel and nuclear waste shall be implemented so that biodiversity and the sustainable use of biological resources are protected against the harmful effects of ionizing radiation.

Biological effects of ionizing radiation in habitats and ecosystems concerned shall be described. The report shall be based on available knowledge on the ecosystems concerned and shall take particular account of the existence of genetically distinctive populations such as isolated populations, endemic species and species threatened with extinction and in general any organisms worth protecting.” (§§ 6-7)

In order to determine whether or not the requirements are met, knowledge is required of the ecosystems that are (or may be) affected and of biological effects in the organisms that occur in the ecosystem.

2.2.6 Requirements on the Safety Assessment for Different Time Periods

A description of the radionuclide transport to and within the biosphere is necessary for an assessment of health and environmental protection. Geological conditions in a long-term perspective can be described in a different manner than man and the biosphere. SSI has therefore requested reports for two different time periods.

The First Thousand Years
For this time period, a description can be prepared, based on quantitative calculations. SSI places high demands on the basis of the description and SSI's view is that calculations should be performed on the basis of reasonably predictable conditions. For this period, it is assumed that the calculations are based on the properties of the present-day biosphere and that known and ongoing changes, such as land elevation, are taken into account.

Longer Time Periods
Many components can and must be described in a long-term perspective. However, licensing must not be dependent on endless discussions regarding the living habits and environment of humans in a remote future. SSI therefore requires that the "description shall include a case, which is based on the assumption that the biosphere conditions which exist at the time when an application for a licence to construct the repository is submitted will not change".

This means that, in this case, the description must be based on present-day conditions with respect to the general properties of the biosphere and human living habits. The geological land elevation is a change in the biosphere which should be taken into consideration in all appropriate time frames. Furthermore, the impact on the repository from a glaciation cannot be excluded from the analysis. The use of the present-day biosphere in a case is to be interpreted to mean that since it is difficult to predict the biosphere conditions after an ice age, the present-day biosphere is to be used as a reference when calculating the dose consequences for all time periods.

2.3 Safety Requirements

2.3.1 Overview

One result of SKI and SSI's co-ordination of regulatory work was that the authorities together presented their plans for regulations on final disposal in 1997. This took the form of formal review processes involving the nuclear power industry, SKB, other authorities and the municipalities concerned. The material compiled by SKI and submitted to formal review (SKI dnr. 5.8-970478, March 24, 1997, *SKI's Premises for Regulations and General Recommendations concerning the Final Disposal of Spent Nuclear Fuel etc.*) was a memorandum that described the content of the regulations and general recommendations in detail. It should be emphasized that the content of the current draft regulations (2000) is only marginally different from the content of this memorandum from 1997. Thus, SKI's view on the requirements that should be made on a repository and on the safety assessment has in principle been well known, at least since 1997.

In August 1998, SKI promulgated its regulations concerning the safety of certain nuclear facilities (SKI FS 1998:1). The regulations entered into force on July 1, 1999. These regulations also apply to the construction, operation and closure of a repository. However, they mainly focus on safety during operation and provisions must be added with respect to the long-term safety after closure. An initial version of supplementary regulations on final disposal, adapted to SKI FS 1998:1, was subjected to a limited formal review by the nuclear power industry, SKB and SSI in June 1999. This version (dated July 20, 2000, SKI dnr. 5.1-990760) which was subjected to a complete formal review in 2000 is only marginally different from the previous version.

2.3.2 Basic Safety Requirements

The intention behind SKI's draft regulations is compliance with the requirement on an adequate containment of the radioactive substances for as long as necessary, taking into account the hazardous nature of the waste. Safety is to be attained through a system of barriers. Each physical barrier, such as a concrete wall can, in turn, have one or more functions in the repository. A breach in one of these multiple-barrier functions may not tangibly degrade repository safety.

A passive barrier system may comprise one or more barriers with barrier functions that interact to provide the system with an adequate isolation capability for a sufficiently long period of time. Engineered (man-made) barriers and the natural barrier in the form of rock may be accounted for as barriers of the system.

The site of a repository in rock, including repository depth, should be selected so that the rock will provide adequately stable and favourable conditions for the intended performance of the repository barriers over an adequately long time. The conditions intended primarily concern the temperature (including present-day and future climates), permeability, rock mechanics and geochemistry.

SKI's draft also refers to the basic requirements on the protection of human health and the environment that have been stipulated in SSI's requirements on the protection of human health and the environment in connection with the final disposal of spent nuclear fuel and nuclear waste.

Furthermore, in the general recommendations to SKI's proposal, SKI emphasizes that risks from final disposal cannot be predicted exactly, but must be estimated on the basis of the view of risk obtained from an integrated assessment of consequences and probabilities of different future events (scenarios). This view of risk should be presented in a report of calculated or otherwise estimated consequences and probabilities for a selection of relevant scenarios. The consequences must be taken into account or estimated for a number of cases so that the resulting view of risk also takes into account the uncertainties of the assumptions and data upon which the calculations or estimates are based. The selection of scenarios should be such that, taken as a whole, they provide a comprehensive view of the risks associated with the repository.

2.3.3 Design and Construction Requirements

The requirements made with respect to the design and construction imply that the barrier system must be sufficiently robust to withstand those features, events and processes that can impair its performance.

The draft regulations also contain provisions that agree with SSI's requirements that the repository should be designed and constructed with respect to the best available technique as well as the requirement on reporting the impact of measures that are (may be) taken to facilitate monitoring and retrieval or to make intrusion into the repository difficult.

2.3.4 Requirements on the Safety Assessment

Content of the Safety Assessment
SKI's draft regulations require that features, events and processes that are important to safety should be analyzed before the repository is constructed, before it is taken into operation and before it is closed. The published SKIFS 1998:1 regulations also require that the safety assessment should be kept up-to-date and that a new safety assessment should be performed once every ten years, for as long as the repository is in operation.

SKI's draft regulations place requirements on the documentation of the safety assessment and particularly on the following information:

- ***Analysis Methods***
  An account of how one or more methods have been used to describe the passive system of barriers in the repository, its function and evolution over time. The method or methods must contribute to providing a clear view of the features, events and processes that can affect barrier performance as well as the inherent links between these features, events and processes.

  An account of how one or more methods have been used to identify and describe relevant scenarios for event sequences and conditions that can affect the evolution of the repository.

  An account of how uncertainties in system description, scenarios, calculation models and calculation parameters as well as variations in the barrier properties of the rock have been treated in the safety assessment, including an account of a sensitivity analysis that shows the impact of the uncertainties on the description of the barrier evolution and the analysis of the consequences to human health and the environment.

- ***Analysis of Post-closure Conditions***
  An account […] including descriptions of the evolution of the biosphere, geosphere and repository in selected scenarios. An account of the impact of the repository on the environment with respect to selected scenarios, taking into account possible defects with respect to engineered barriers and other identified uncertainties.

Scenarios
The general recommendations to SKI's proposal are particularly detailed with respect to recommendations on how the safety assessment should be performed and documented. Therefore, different categories of scenarios should be used to assess the performance of

the repository during varying internal and external features, events and processes (FEPs):

- A *main scenario* which should be based on the probable evolution of the biosphere and realistic assumptions on the barrier properties. Furthermore, it should be based, as far as possible, on probable assumptions on internal FEPs, including justified assumptions concerning the occurrence of manufacturing defects and other imperfections and which allows for an assessment of the repository barrier performance. (For example, it is not sufficient to always assume that the waste packages will be leaktight for a long period of time, even if this is the most probable case). The main scenario should be used as the basis for analyzing the influence of uncertainties (see below), which means that the analysis of the main scenario will contain a number of calculation cases (cf. the requirement on sensitivity analysis, below).

- A number of *less probable scenarios* for the assessment of scenario uncertainty including alternative event and time sequences as well as scenarios to investigate the impact of damage to barriers as a result of future human intrusion.

- *Residual scenarios* which should be selected and studied in order to determine the importance of individual barriers and barrier functions. Residual scenarios also include cases to determine damage to human intruders into the repository as well as cases to determine the consequences of an unclosed and unmonitored repository. These scenarios cannot be directly used as a basis for assessing the safety of the repository and certain scenarios should be evaluated primarily from the standpoint of comparisons with alternative methods for nuclear waste management.

Probabilities that scenarios and calculation cases will actually occur should be estimated as far as possible, even though the estimates cannot be exact. In this context, is necessary to support arguments using different methods, such as the judgements of a number of independent experts (e.g., expert elicitations). For example, this can be achieved by estimating the time when different events are expected to occur.

On the basis of important scenarios, a number of *design basis cases* should be identified. Together with other information, such as manufacturing techniques and controllability, these cases should be used to determine which requirements should be met with respect to barrier properties.

Uncertainties
According to SKI's draft regulations, the analysis of uncertainties, namely deficiencies in knowledge and other uncertainties in the calculation assumptions is an important part of the safety assessment. The uncertainties that must be examined relate to scenario selection, the completeness of system descriptions, input data, calculation models and the spatial variation of the rock properties. These types of uncertainties should be described and treated in a consistent and structured manner in the selection of calculation cases, calculation models and parameter values as well as in the evaluation of calculation results.

Calculation Models
The assumptions and calculation models used should be carefully selected taking into account how they will be applied and the selection justified through a discussion of alternatives and references to scientific data. If there is any doubt about which model is suitable, several models should be used to determine the effects of uncertainties in model selection. Both deterministic and probabilistic methods should be used so that they supplement each other and, in this way, provide as comprehensive a view of risk as possible.

The validity of models, parameter values and other assumptions used should be shown through references to scientific literature, special investigations and research results, laboratory experiments on different scales, field experiments and studies of natural phenomena (natural analogues). Scientific data and expert judgements should be documented in a traceable manner.

Time-related Aspects
According to the draft, the post-closure safety assessment should cover as long a period of time as the safety functions are required. However, the period covered may not be less than ten thousand years, although it does not have to exceed one million years. (This limitation has been introduced in view of the uncertainties associated with rock properties which mean that it is not reasonable to perform an assessment for longer time-scales.)

In the case of a repository for long-lived nuclear waste, a safety assessment may have to include scenarios that take into account major expected climate changes, mainly in the form of future glaciations. For example, particular attention should be paid to the next complete glacial cycle – estimated to be on the order of 100,000 years.

According to SSI's regulations, for periods up to 1,000 years after repository closure, the dose and risk calculated for present-day conditions in the biosphere should be used to assess the safety and protective capability of the repository. For longer periods, the assessment should include dose as one of several safety indicators and for several possible biospheres. This should be taken into account in calculations as well as in the presentation of the analysis results. An example of such supplementary safety indicators is the concentration of radioactive substances from the repository that can accumulate in the soil and near-surface groundwaters. In this case, the occurrence of natural radioactive substances can be a basis for determining what is tolerable in these respects. Another example is the estimated outflow of radioactive substances to the biosphere which can be placed in relation to comparable natural radioactive flows.

2.4 Basis for the Regulatory Review of SR 97

The authorities have evaluated SR 97 from the standpoint of the regulations promulgated by the authorities, discussed in Section 2.4.1, and from the standpoint of the purposes of SR 97 which have been stated by the authorities and the Government, discussed in Section 2.4.2.

2.4.1 Overall Requirements on Safety and Radiation Protection

The safety and radiation protection requirements described in Section 2.2 and 2.3 must be met no later than before the construction of a repository. However, as shown in Section 2.1.1, these requirements do not necessarily have to be met at this stage, which is about one decade before the start of construction and many years before the final licensing. However, it is reasonable to demand that the safety assessment and the independent peer review of the assessment should show that there is no unresolved issue that would seriously prevent compliance with the requirements at the time of licensing. In fact, SKB's report should show that it is probable that the requirements can be met. This is in line with SKI's statement to the Government on RD&D Programme 98, where SKI states that the purpose of SR 97 is "to show that KBS-3 would have good prospects of meeting the long-term safety and radiation protection requirements that have been specified by SKI and SSI in recent years", cf. Section 1.2.

An evaluation of the compliance with these requirements can be broken down into three questions:

- Is the methodology used for safety assessment sufficiently developed to allow an assessment based on a complete background material?
- Are there any deficiencies in the knowledge base presented and in the technical basis, or has any knowledge emerged during the independent peer review that indicates that the KBS-3 method would not be able to meet the overall requirements?
- Is the consequence analysis adequate, bearing in mind the current stage of the programme?

The importance of the first two points can be seen by the fact that it is not only the calculated and reported consequences (mainly in the form of radiation dose) or risks that are of decisive importance, but what is at least equally important is *how* (methodology) and *which* background knowledge (of processes and materials properties etc.) have been used to develop these measures of consequences.

Review of Safety Assessment Methodology

The methodology used in SR 97 does not have to be developed in detail. Nevertheless, in SR 97 SKB must demonstrate the methodology and its application so that it is clearly shown that this is a feasible approach and that the methods used are adequate, taking into account the role of the safety assessment in guiding and evaluating site investigations. The demonstration of methodology should relate to the following factors:

- A logical and well-structured method for the identification of FEPs that is transparent, that can be documented in a traceable manner and that facilitates the evaluation of completeness and judgements made by SKB's experts.
- A logical and well-structured method for scenario selection and definition of calculation cases.
- A treatment and evaluation of uncertainties that is adequate (such as the use of alternative models, sensitivity analysis, the identification and evaluation of remaining uncertainties).
- The use of relevant indicators for the future consequences of the repository.

- A reasonably well-developed method for the treatment of risk and risk estimates.

Methodological issues also include the structure of the report and the presentation of the safety assessment.

Review of the Knowledge Base and Technical Basis

The issue of deficiencies in knowledge is partly related to methodology. A complete safety assessment methodology should allow the assessment to be complete in that the extent to which the overall safety and radiation protection requirements are met is evident. Additional information or clarifications should not be necessary. A methodology that is underdeveloped or that is incompletely applied places greater demands, in practice, on the review. However, the reviewer must never assume the responsibility for the safety assessment from the proponent.

The safety assessment is based on general knowledge, such as well-established technical and scientific methods, data and models, and more specific knowledge with respect to the technical basis such as the properties of the engineered barriers and of the rock. In the former case, it is reasonable to demand that sufficient data should be produced at a relatively early stage of the final disposal programme. In the latter case, it is not reasonable to demand that all information should be prepared at such an early stage. This is particularly the case for the properties of the rock at a site that has not yet been investigated. However, information should be available that demonstrates the feasibility of locating rock with suitable properties.

The properties of the engineered barriers that are considered preferable are dependent on the requirements that are made on the basis of the reliability of the other barriers and the hazard of the waste and other properties. Such preferable properties (design basis requirements) can be derived with the help of the safety assessment. In recurrent assessments, such as SR 97, SKB should show whether the assumptions used are adequate (such as the permitted number of initially defective canisters). However, this would require a complete analysis of scenarios and uncertainties. An additional and equally important matter to assess is whether or not these properties are feasible.

In the review of the information presented in SR 97 from these two perspectives, the important factor is that no serious indication should be found that a safe repository cannot be constructed using the specified method. This primarily applies to:

- Knowledge that indicates the feasibility of the repository's technical properties
- The application of models for the evaluation of the barrier and system properties that have been shown, in an acceptable manner, to be suitable in the cases considered (models for heat transport, hydrology, rock mechanics and geochemistry etc. that have been adequately validated).

For practical reasons, it may be suitable to implement and report the methodology and its application in one and the same context. This particularly applies to

- completeness of the treatment of FEPs
- adequate identification of uncertainties
- selection of scenarios that are adequate in terms of scope and relevance

The authorities' overall evaluation, presented in Chapter 5, has been performed in this way.

Consequence Analysis

The final stage in the safety assessment is the calculation of the environmental consequences in order to demonstrate compliance with the protection requirements. The methodology and facts are to be used to select calculation cases for different scenarios based on the results obtained from the sensitivity analysis and other uncertainty analyses. Various calculation models are used most often to calculate radionuclide transport in the system of engineered barriers and the near field, the geosphere far field and the biosphere. Probabilistic models are also used to assess risk which take into account probabilities in the selection of input data and other assumptions used in the calculations. The review of the consequence analysis primarily concerns the following factors:

- Whether or not the level of detail in the analysis is adequate for the relevant time periods.
- Whether or not the selection of calculation cases for various scenarios and uncertainties is adequate.
- Whether or not the models for radionuclide transport in the geosphere and biosphere are adequately supported
- Whether or not relevant measures of the protective capability of the repository have been applied, including safety indicators that supplement dose and risk in long timeframes (>1,000 years).

The consequence analysis can also be evaluated in the same context as the methodology, as has been done in Chapter 5 of this review report.

2.4.2 Specific Purposes of SR 97

As stated in Section 1.2, in addition to showing that KBS-3 would have good prospects of meeting long-term safety and radiation protection requirements, SR 97 should fulfil a number of different specific purposes. The basis for the review with respect to each of these purposes is described below.

To demonstrate the feasibility of finding a site in Sweden that meets the requirements

The feasibility of finding an acceptable site was already established in SKI's review of KBS-3 1983-84 (SKI dnr. 7.3.1-633/83, page 9; February 23, 1984, *Statement to the Ministry of Industry*). The purpose of SR 97 should be interpreted so that it should be clear whether this conclusion is still valid based on present-day knowledge. At the same time, it is evident that complete knowledge can only be achieved through actual site investigations.

To provide a basis for site investigations

The purpose is that, on the basis of SR 97, it should be possible to determine which kinds of investigations are necessary and the level of quality to be maintained in the measurement programmes. It is well known which investigations can be performed and this does not have to be specified further. On the other hand, the importance of different types of information has not yet been determined. In order to do this, it is necessary to conduct comprehensive analyses which can provide guidance as to which investigations should be given priority. However, in order to reach more definite conclusions, a broader basis of information is required than can reasonably be demanded of a single safety assessment.

To provide data for the specification of function requirements with respect to the barriers

In the same way that the safety assessment can be used to formulate requirements on the rock and site investigations, it can be used to formulate design basis requirements in the form of function requirements, technical requirements and testing and control programmes for the engineered barriers (cf. Sections 2.1.1 and 2.2.6). This was also one of the aims of SR 97. Once again, it is the completeness of the assessment that determines the extent to which such a purpose can be fulfilled. A complete set of requirements must be prepared no later than before the repository is taken into operation. However, it is important that the more basic function requirements should be identified during the current stage of the programme, particularly so that they can be used to guide work in the RD&D programme.

To contribute to the specification of site selection factors

The geological site selection factors intended here can be specified through SR 97 only on the basis of differences in the properties of the rock at the sites included in the study. The review should determine whether the site evaluations are adequate in this respect.

3 SKB's Safety Strategy and Interpretation of the Regulatory Requirements

3.1 Introduction

In Chapter 2, SSI and SKI's regulations were described. These regulations establish certain premises for SKB's safety assessment. The regulations are of a general nature which means that SKB must interpret them. The authorities' evaluation of SKB's interpretation is presented in this chapter. SKB has also formulated its own overall safety strategy which is also evaluated below. The purpose is to judge whether SKB's strategy complies with the basic regulatory requirements on safety and radiation protection.

A number of regulatory requirements were developed and promulgated in parallel with SKB's work on SR 97. Although this primarily applies to SKI's regulations, it also applies to a certain extent to SSI's.

As far as the protective goals relating to human health and the environment, SSI discussed the environmental aspects as early as during the first draft of SSI's radiation protection criteria for a repository (SSI, 1995). In the later draft of SSI FS 1998:1, SSI argued for a dose criterion, 10 µSv annual mean dose to individuals in the critical group. SSI stated the following in its comments (SSI, 1997):

"The aim is to obtain an estimate of the mathematical expected value of the individual dose. This means that a higher dose than the restriction can be accepted as a calculation case, if the proponent can show that the likelihood of an event sequence is so low that the expected value for the individual dose does not exceed the constraint".

In principle, this corresponds to a risk calculation as later defined in (SSI, 1999), see Section 2.2.4. On account of this and on account of the fact that the analysis of scenario probability is a natural part of a safety assessment, the authorities do not consider that the fact that SSI's regulations were promulgated in September 1998, could have fundamentally changed the direction of SKB's work. On the other hand, the regulations provided clear protective goals for SKB.

The evaluation of the regulatory authorities presented in this chapter is largely based on the review of Chapters 2 and 3 and Section 5.7 of SR 97. The evaluation also discusses some issues not treated by SKB in SR 97. Some of these issues (such as environmental protection and collective dose estimates) will have to be included in the safety assessment in future, while other issues are better dealt with outside the safety assessment (such as optimization and BAT).

3.2 Comments by the Reviewing Bodies

The reviewing bodies have only, to a very limited extent, dealt with SKB's interpretation and application of the authorities' regulations. One exception is SSI's risk criterion, which is discussed by several reviewing bodies as well as by some of SKI's consultants (SKI, 2000c). However, the opinions relate to modelling and calculation and not to the interpretation of the criterion, as a matter of principle. Consequently, these views are discussed in Section 4.3.10, which deals with risk assessment and probabilistic calculations.

In KASAM's view, the only acceptance criterion that SKB uses in SR 97 is SSI's risk constraint and it is debatable whether this is sufficient. According to KASAM, there are other criteria which can be applied, such as environmental impact or the supply of material and competent labour. Acceptance would then be determined by taking into consideration all of the criteria as a whole.

3.3 SKI and SSI's Review and Evaluation

3.3.1 Health Protection

After reproducing SSI's regulations on health and environmental protection (SSI, 1999), SKB states that these were promulgated at a late stage in the work on SR 97. With respect to SSI's requirements on individual protection, formulated as a highest permissible annual risk of 10^{-6}, SKB emphasizes SSI's commentary (SSI, 1999) to the regulations where it is stated that:

"If the proponent wishes to calculate the dose to an individual who is considered to have a high dose commitment, it may be acceptable to perform the calculations for an individual who represents the higher level within the range, instead of an individual who is representative of the dose commitment for the entire group."

The range is an interval for an annual risk that can have a 10^{-7} to 10^{-5} variation across a regional group.

The authorities are conscious of the fact that SKB in its work would rather use a "hypothetical individual" with a 10^{-5} annual risk instead of the regulatory level of $10^{-6.}$ However, the authorities would like to emphasize that arguments must be presented that show that the hypothetical person actually represents the higher level within the range, namely that in the selected case, the risk to the individual in a large group would be around 10^{-6}. This is discussed further in Section 4.3.9.

The IRT, which in its review finds that SKB's methodology for risk calculations is not complete, points out the need to investigate the risk criterion in greater depth and, particularly, its application (SKI, 2000a). The IRT emphasizes that further dialogue is required between the authorities and SKB to develop the application of the risk criterion. The authorities share this view and will continue to discuss the issue with SKB.

3.3.2 Environmental Protection

In the authorities' view, SKB has understood the environmental protection goals in SSI's regulations. Furthermore, the authorities share SKB's view of the state of the field, for example, the lack of established international guidelines.

The absence of clear international evaluation criteria within environmental protection means that SKB must itself provide the impetus for work in the area in order be able to fulfil the authorities' requirements in connection with a future licence application for the construction of a repository. This is discussed in greater detail in Section 4.3.9.

3.3.3 Time-frames

SKB comments on SSI's special reporting requirements for the first thousand years. An important reason given by SKB is the fact that 99% of the radioactive substances will have decayed during this time. SSI gives additional reasons in the commentary on its regulations (SSI, 1999). The authorities consider that it is not clear that SKB has covered the thousand-year time-frame with the degree of thoroughness that the relatively short time-frame should allow. It should also be in SKB's own interests to better describe the foreseeable future, a time period that involves our children and grandchildren and which should obviously be important. One possibility of better describing the thousand-year time-frame could be to describe and analyze the scenarios that could result in doses to individuals during this time-frame.

SKB does not explicitly discuss the requirements on an analysis for a longer time-frame, as specified in SKI's draft regulations. In the authorities' view, SKB nevertheless deals with this issue in an appropriate manner in the following respects:

- no absolute upper boundary for the period of time the analysis should cover is specified. On the other hand, calculations are performed up to a period of 1 million years
- SKB states that the approach that it has taken is that the repository must function for as long as it is hazardous.

3.3.4 Biosphere Conditions

In the authorities' opinion, the work on safety and radiation protection should not be dependent on speculations on what a remote future would look like. SSI has therefore required that the safety assessment should include a case with an unchanged biosphere. SKB has commented on this stipulation in its analysis of regulatory requirements.

However, it was not SSI's intention that scenarios such as a glaciation, which would make an unchanged biosphere impossible, should be excluded from the safety assessment. For such cases, the authorities take the view that SKB should use the present-day biosphere and society after the event, such as a glaciation, to investigate the effects of a radioactive outflow from the repository.

3.3.5 SKB's Safety Criteria and Safety Strategy

During the development of KBS-3, especially in connection with the reporting of its programme, SKB has defined various requirements that the repository should meet, such as safety principles and various performance requirements for the repository components. In order to have a discussion on these issues which can be understood by non-experts, a terminology, consistently applied by all of the parties involved is necessary. In consultation with the authorities, SKB should develop such a terminology.

The IRT (SKI, 2000a) also discusses SKB's safety strategy and finds that SKB has developed a robust final disposal concept, based on multiple barriers. According to the IRT, the strategy is so flexible that new scientific and technical advances can be used to develop the final disposal concept.

The IRT also discusses how the safety strategy should be presented. In the IRT's view, SKB needs to have a high-level strategy document that summarizes its safety strategy. Such a document would be updated as new knowledge is gained, as the strategy changes and as essential safety-related issues emerge. The IRT's opinion is that, on the whole, a strategy document would promote a common understanding within SKB of the programme objectives and status, facilitate the company's dialogue with the safety authorities and provide a coherent description to a broader public. SKI and SSI have also recognized the need for such a document. This document could also serve to establish the terminology requested above so that different types of requirements and criteria can be placed in their context at different stages of construction and operation of a repository, such as safety indicators, performance requirements, technical criteria and technical specifications.

In Section 5.7, SKB presents its safety criteria, which partially correspond to quantitative and qualitative performance requirements on the different barriers: the canister, buffer, backfill and rock. SKB states that the purpose of the safety assessment is to show that these criteria are met. However, this is not sufficient, it must also show that the safety criteria comply fully with the regulatory requirements. In SKI's draft regulations for safety in connection with final disposal, the general recommendations state that the safety assessment should contain a number of design basis cases to demonstrate this issue. In the authorities' opinion, a documented safety strategy would be useful in this context.

In summary, it can be stated that there is no major difference in the authorities' and SKB's view of safety criteria. However, greater rigour is needed with respect to terminology and how these terms are handled and used in the various stages of a final disposal programme.

3.3.6 Optimization and BAT

SKB reproduces § 4 of SSI FS 1998:1 concerning optimization and mentions the requirements regarding the calculation of the collective dose. SSI would like to reiterate that the optimization requirement has been formulated taking into account the fact that the regulations apply to more than just final disposal in accordance with the KBS-3 concept, namely, any form of final disposal, even final disposal alternative such as transmutation. In connection with transmutation, the collective dose from C-14 would play an important role in assessing radiation protection

In the case of final disposal, optimization is not possible in the classical sense that improvements in radiation protection must be made if the collective dose can be reduced by a given efficiency, expressed in SEK/mansievert. This would mean that doses over very long time periods would have to be assessed in order to direct present-day costs. In a time-frame of one million years, for example, not only is the dose uncertain, it is not even clear what species would be exposed to radiation.

On the other hand, the concept of optimization can be perceived as a general attempt to reduce radiation doses. If SKB perceives any possibility of improving the final disposal method at a reasonable cost, the improvement should be made. In terms of a remote future, this requirement corresponds to the best available technique (BAT).

It must be emphasized that optimization is not primarily a task to be conducted when analyzing the long-term safety of a repository. All of the stages in the final management of the waste must be taken into account and weighed together in the optimization process. In the case of the KBS-3 method, this means that radiation doses to personnel and to the public from the encapsulation, transport and operation of the repository must be included with any dose exposure from a closed repository in a remote future. Optimization is therefore primarily a task to be undertaken when assessing the performance and safety of the entire final disposal system, as is SKB's responsibility.

For the same reason as for the optimization, the application of BAT is not a task to be conducted in the safety assessment, but should be reported in separately by SKB. It should be added that BAT is now a requirement, not only in SSI FS 1998:1, but as of 1999, also one of the "general rules of consideration" of the Swedish Environmental Code. In its future final disposal regulations, SKI will also place requirements on the application of BAT for the design and construction of the barrier system in a repository. Even if both optimization and BAT are largely beyond the scope of the safety assessment, SKI and SSI both consider that it would be justifiable for SKB to initiate work and a dialogue within these two areas with the authorities.

4 Safety Assessment Methodology and Its Application in SR 97

In this chapter, the authorities present their overall evaluation of SKB's safety assessment methodology and how it is applied in SR 97. Detailed comments on SKB's description of processes and initial states and on SKB's description of the various scenarios are presented in Appendix 1 and 2, respectively. The appendices contain larger number of examples and more detailed arguments in support of the overall evaluation presented in this chapter.

4.1 SKB's Report

In SR 97, one chapter is dedicated to methodology (Chapter 4 of the Main Report). In this chapter, an overview is presented of the various stages and analysis methods of the safety assessment. However, the methodology for the calculation of radionuclide transport and risk analysis is reported directly in the canister defect scenario (Chapter 9) and is also discussed to a certain extent in the concluding chapter (Chapter 13). The implementation and reporting in SR 97 are divided into five main stages:

1. System description
2. Description of the initial state
3. Scenario selection
4. Analysis of selected scenarios
5. Evaluation.

In SR 97, SKB presents a new way of structuring the system description using processes and variables in THMC diagrams (Thermal, Hydraulic, Mechanical and Chemical processes). The identified processes are described in a background report ("Processes in the Repository Evolution", TR-99-07). Furthermore, the description is structured so that the various variables in the THMC diagrams are assigned initial values. The initial state is a description of the repository state immediately after closure, namely a description of the properties of all of the repository parts, including the repository site. This description is reported in a background report ("Waste, Repository Design and Sites", TR-99-08) and in Chapter 6 of the main report.

In SR 97, SKB presents analyses of five scenarios: a base scenario, a canister defect scenario, a climate scenario, an earthquake scenario and a scenario that deals with future human actions. SKB states that the selection of these scenarios is based on experience from previous safety assessments and on the system description. Calculations of radionuclide transport are reported for the canister defect scenario and, to a certain extent, for the climate scenario. All input data for the transport calculations in the canister defect scenario are reported in a background report ("Data and Data Uncertainties", TR-99-09). The total risk analysis is based on an argument concerning how the risks associated with the different scenarios can be summed up. However, in practice, the combined risk is based on the result of the canister defect scenario, for which a formal analysis has been conducted.

4.2 Comments by the Reviewing Bodies

The National Council for Nuclear Waste (KASAM) is of the opinion that SKB's work is of a high standard and that the safety issues have been examined in a manner that is as comprehensive and detailed as it is reasonable to demand at this stage. KASAM points out the difficulty of deriving site selection criteria for the geosphere from the safety assessment and comments that SKB has therefore attached overriding importance to the other safety barriers, particularly the canister and bentonite barrier. With respect to the selection of scenarios in SR 97, KASAM's view is that there is a risk that an approach to scenario analysis that is too engineering-oriented could result in a basis for decision-making that is too limited. For example, KASAM emphasizes that even if the prime purpose of SR 97 is to describe the safety of the repository after closure, circumstances that lead to the non-closure of the repository should be included in the safety assessment.

In KASAM's view, uncertainties surrounding the long-term evolution of the buffer in various repository environments should be investigated in greater detail and SKB should make an effort to obtain information for realistic assumptions regarding initial canister defects. KASAM also states that uncertainty intervals must be assigned to certain parameters that could have different values in the bedrock, namely where distribution functions have not been used to describe the variability.

The Geological Survey of Sweden (SGU) is of the opinion that the coupling between glaciations and rock movements is inadequately studied in SR 97. SGU also considers the safety assessment to be too hypothetical and that a final safety assessment can only be performed when data have been obtained from the site or those sites that are considered to have good prospects of hosting a deep repository.

Pereira, Stockholm University, is of the opinion that SKB has the necessary computer tools to perform probabilistic analyses but states that they should be used to conduct a more complete risk analysis than that presented in SR 97. Pereira also states that the report on "Data and Data Uncertainties" should be supplemented so that SKB can conduct a more complete risk analysis. According to Pereira, the reported deterministic calculations should have been supplemented by other parameter combinations in order to investigate synergies. Pereira also states that the use of discrete distributions with two values decreases credibility and questions SKB's conclusion that the form of the calculated dose distributions can be taken as an indication of the robustness of the system.

The Royal Institute of Technology, Stockholm (KTH) considers that it would have been of value if the screening process for scenario selection had been described and if the eliminated scenarios had been described.

4.3 SKI and SSI's Review and Evaluation

4.3.1 Introduction

The authorities agree with SKB that there is no standardized method for performing a safety assessment for a spent fuel repository. The authorities take a positive view of the fact that SKB is participating in international work, such as within the OECD/NEA, to ensure that the safety assessment methodology is updated and comprehensive.

The authorities find that SKB's safety assessment methodology has improved within several important areas, such as with respect to:

- the documentation of the processes and properties, with associated uncertainties, that can affect repository performance
- the reporting of input data for the consequence analysis
- the development of knowledge and models for the evaluation of initially defective canisters
- the more detailed evaluation of the biosphere.

Furthermore, with SR 97, SKB has taken a first step towards adapting its safety assessments to the regulatory requirements, such as with respect to the presentation of the protective capability of the repository in the form of risk. The authorities intend to continue a dialogue with SKB concerning the implications of the detailed safety and radiation protection requirements in their regulations.

At the same time, in their review below, the authorities state that certain parts of the methodology presented in SR 97 must be developed and detailed prior to future licensing. The authorities also emphasize that SKB's development of safety assessment methodology is an ongoing task that should continue throughout all of the stages of repository construction. The authorities intend to return with additional opinions on the reporting that is necessary prior to the various stages of SKB's final disposal programme in connection with upcoming reviews of SKB's Programme for Research, Development and Demonstration (RD&D Programme).

4.3.2 Structure and Presentation

The authorities share the opinion of the IRT (SKI, 2000a) and KASAM (SKI, 2000b) that the SR 97 Main Report is, on the whole, well written and organized. The structure – with background reports focusing on processes, data and the repository system – provides a good overview even if some parts of the text, such as the hydrogeological description, are repeated in several places. In their overall evaluation, the authorities also state that SR 97 contains the components that, according to SKI's draft regulations and SSI's regulations, must be included in a safety report for a repository for spent nuclear fuel (see Chapter 2).

With respect to the presentation of SR 97, the most important criticism of the authorities and the IRT concerns deficiencies in the traceability and transparency of different types of judgements made. These issues are further discussed in Section 4.3.11. Another deficiency, which is also mentioned by SKB, is that the description of the selection of scenarios and the method for risk calculations will have to be improved prior to future safety reports (see also Section 4.3.10).

In the authorities' view, the description of biosphere processes and biosphere models has not been adequately reported in the SR 97 Main Report and background reports. This information must, in all essential respects, be taken from sub-references.

SR 97 is based on the template that SKB previously presented in SR 95 – Template for Safety Reports with Descriptive Examples (SKB, 1995). The authorities support SKB in its ambition to use a permanent basic structure (template) for its safety reports. A large part of the basic documentation, such as the system description and method description, would then only have to be updated for new safety reports. This would facilitate the regulatory review and make it easier to identify what new information has been added in relation to previous safety assessments. In conclusion, the authorities encourage SKB to review the structure of its safety reports with respect to the experience gained from SR 97 and the critical findings of this regulatory review.

4.3.3 Focus of the Safety Assessment

The IRT (SKI, 2000a) states that the KBS-3 method is based on an internationally accepted safety strategy with multiple long-lived barriers and that SKB's safety assessment is supported by an extensive research and development programme that is well adapted to a development of the repository in stages. The IRT is also of the opinion that SR 97 provides a good illustration of the safety of the KBS-3 method even if the traceability and completeness of the argumentation can be improved.

The IRT also consider that SKB should be clearer in the description of its strategy to achieve and demonstrate safety. The IRT also propose that SKB should conduct safety assessments more often in the future and that the safety assessment's role in integrating the different parts of the final disposal programme should be reinforced. KASAM (SKI, 2000b) is of the opinion that SKB should be clearer in reporting the basic ethical and value judgements in the safety assessment.

In the authorities' opinion, SR 97 contains the components required for a comprehensive description of safety and radiation protection. However, the authorities agree with the IRT that SKB should clarify the role of the safety assessment in fulfilling different purposes. In SR 97, SKB has placed considerable emphasis on the purpose of showing that the KBS-3 method can meet SSI's risk criterion. However, the authorities consider that the purpose of providing a basis for deriving requirements on site investigations and the engineered barriers has not been given sufficient scope (see Section 4.3.12).

In the chapter on methodology (Chapter 4), SKB states that in SR 97, the aim was to place greater focus on the isolating functions of the repository, compared with previous safety assessments. This is reflected in the analyses of the properties of the engineered barriers (near field) and their future evolution in the base scenario. SKI's consultant, Voss (SKI, 2000c) is of the opinion that the assumptions for the functions of the near field are far too optimistic. In his view, this has meant that the importance of the rock to safety has not been adequately tested in SR 97. Wörman and Xu (SKI 2000c) would generally like to see a clearer description of how different barrier functions in the near field and geosphere contribute to repository safety.

In the authorities' view, the focus on the isolating functions of the repository should have resulted in a more comprehensive analysis of the uncertainties associated with the long-term evolution of the near field. However, the authorities emphasize that it is the combined performance of all of the barriers that is decisive in an assessment of safety and radiation protection.

The authorities share the view of Tsang and Voss (SKI, 2000c) that SR 97 does not focus sufficiently on the evaluation of unfavourable conditions or combinations of unfavourable conditions. The authorities find that several potentially unfavourable FEPs are rejected at an early stage of the analyses (in the background report "Processes in the Repository Evolution"), without their possible importance to the risk analysis having been evaluated (see also 4.3.4 and 4.3.10). In the authorities' view, SKB should ensure that it describes the safety margins of the KBS-3 method by illustrating the repository's capability to withstand hypothetical and less probable events, which can include calculation cases that result in higher doses.

SKB states (in Chapter 3) that it does not include dilution and migration in the biosphere as a safety function, and refers to the difficulties of predicting the evolution of the repository. At the same time, dilution in the biosphere is a decisive factor for the assessment of the consequences of the climate scenario. In the authorities' opinion, SKB should define the biosphere's role, in consultation with the authorities, prior to future safety assessments.

Finally, the authorities have noted that SKB has chosen not to describe the safety-related couplings between the repository for spent nuclear fuel and the repository for other long-lived waste in SR 97. The authorities have learned that is due to the fact that SKB has chosen to completely disassociate the siting processes for these two repositories from each other. However, if SKB has not definitely eliminated the possibility of co-siting the two repositories, the impact that the two repositories can have on each other should be described.

4.3.4 System Description

The system description is the structured description of the features, events and processes (FEPs) that must be taken into account in order to be able to describe the evolution of the repository barrier system and its performance in different scenarios. In SR 97, SKB presents a new way of structuring the system description with processes and variables in THMC diagrams (Thermal, Hydraulic, Mechanical and Chemical processes). The identified processes are described in the background report, "Processes in the Repository Evolution".

In the authorities' opinion, the systematic review of processes and data presented in "Processes in the Repository Evolution" and in "Data and Data Uncertainties" reports is necessary to ensure traceability. However, the relationship between these two reports is not achieved in such a way that together, they provide an adequate and clear view of the assumptions for the safety assessment calculations. However, it must be emphasized that considerable progress has been made in the handling of traceability in SR 97.

In SR 97, SKB has chosen not to include the processes in the biosphere in the format for the system description that has been developed for the processes in the engineered barriers and the geosphere. The authorities see no reason why the processes in the biosphere should be treated separately in this respect.

SKB's system description is based on internationally available lists of FEPs that could affect safety. In the authorities' opinion, the judgements used to exclude certain FEPs should be better supported by well-documented expert judgements and references to scientific data or through a clear structure and sub-references (see Section 4.3.11). Another approach would be to include calculations in the risk analysis so that the risk contributions can be evaluated.

The methods used for system description (besides the THMC diagrams, primarily influence diagrams and interaction matrices) are all complex to understand and use. Therefore, in the authorities' opinion, it is important to continue to develop these methods, primarily so that they can be of better help in the review of the safety assessment. The THMC diagrams share with the other available methods most of the disadvantages pointed out by the IRT and consultants. The most prominent deficiency of the THMC method is that certain relationships are not directly evident from the diagrams. However, again in this case, a better alternative is not yet available.

In conclusion, the authorities view the THMC method as a valuable contribution to safety assessment methodology. The method is not fully developed and can be developed further. However, everything points to the fact that there is still good reason to use different methods within the same programme in order to examine the system description from various angles. The authorities share the opinion put forward by several of SKI's consultants that the expert judgements upon which the diagrams are based must be documented.

4.3.5 Scenarios

In their regulations and general recommendations (see Chapter 2), the authorities state that the scenarios and calculation cases selected for analysis must, together, adequately cover the relevant risks. Therefore, it is important that the risk estimate method, and the purpose of different scenarios, should be clearly described. The coupling between the scenarios selected and the system description should be clear.

Formulation of Scenarios
In SR 97, SKB defines a scenario as: "…the evolution that the final disposal system undergoes, given an initial state and specified conditions in the environment." In SR 97, SKB formulates five scenarios which are separately evaluated in the Main Report.

- A base scenario where the repository is assumed to be built according to specification and where present-day conditions are assumed to persist.
- A defective canister scenario which differs from the base scenario in that a few canisters are assumed to have initial defects.
- A climate scenario that deals with future climate-induced changes.
- A tectonics/earthquake scenario.
- A collective scenario that deals with future human actions that could conceivably affect the deep repository.

SKB bases the selection of scenarios on experience from other safety assessments previously conducted, on work on identifying the FEPs that could affect the final disposal system as well as on work on structuring these FEPs.

The authorities share the opinion of the IRT (SKI 2000a) and SKI's consultants, Wilmot and Crawford (SKI 2000c), that SKB must improve its presentation of the method of formulating scenarios and the purpose of the selected scenarios. It is not sufficient to, as in SR 97, simply state that the selection is based on the experience gained from the work on SR 97 and previous work.

In SR 97, SKB states that the representation of the final disposal system in the form of THMC diagrams can be used to systematically select scenarios and that, prior to future safety assessments, it intends to clarify the relationship between the scenario selection and the system description. The authorities consider that this is essential and necessary development work.

In SR 97, SKB has chosen to treat scenarios based on human intrusion separately. This is in line with SSI's regulations for the final management of spent nuclear fuel and nuclear waste and in line with SKI's draft regulations for the final disposal of spent nuclear waste (see Chapter 2). Comments on SKB's evaluation are provided in Appendix 2, Chapter 5.

Coupling between Scenarios
In SR 97, SKB has opted to separately analyze several of the most important internal and external events in different scenarios. In principle, the authorities have no objection to this approach, provided that the coupling between the scenarios are dealt with in the analyses. One alternative that should be considered is to evaluate more comprehensive scenarios that, in an integrated manner, describe the influence of both internal and external events. Such an alternative would be more consistent with the general recommendations to SKI's draft regulations. The authorities share the view of the IRT (SKI, 2000a) and several of SKI's consultants (SKI, 2000c) that several important couplings between the scenarios in SR 97 have not been reported in a satisfactory manner. Examples include the following:

- SKB's tectonics/earthquake scenario is limited to an analysis of damage to the canister's isolating function during non-glacial periods. The scenario does not take into account an increased frequency and magnitude of earthquakes as a result of future glaciations. Furthermore, the scenario does not describe the effects of rock movements on the transport of radionuclides from a defective canister.
- In spite of the fact that SKB states that climatic conditions other than those assumed to exist in the base scenario will dominate in future, hydrogeological and geological data based on present-day climatic conditions are used for model calculations of copper corrosion and buffer evolution over time periods of 100,000 of years.
- The effect of future climate changes on radionuclide transport is described in very general terms. In SR 97, SKB limits itself to stating that there is an increase in dilution in connection with climate changes and that the effect of an increased outflow of radionuclides will therefore be compensated for by the higher dilution.

Evaluation of Scenario Uncertainty

The analyses of the canister defect, climate and tectonics/earthquake scenarios in SR 97 describe the effects of various events on the repository system. SKB's analyses are a major step towards a complete safety assessment. However, in the authorities' opinion, SKB should perform a more complete analysis of the most important uncertainties in the different scenarios before future licensing.

The authorities would like to particularly emphasize that SKB should evaluate alternative assumptions of the frequency and nature of initial defects in the canister as well as the buffer. For example, in the canister defect scenario, SKB's assumption is that no more than 0.1% of the canisters will have defects that exceed the detection limit. The remaining canisters are assumed to be intact. In the authorities' opinion, SKB should also discuss defects that are below the detection limit and their significance for the long-term integrity of the canister.

Another example is SKB's climate scenario. In SR 97, one climatic development is described, where Aberg is expected to be below water for a very long period of time. However, this assumption is associated with considerable uncertainty. The authorities share the opinion of the IRT (SKI 2000a) and Voss (SKI 2000c) that other climate evolution alternatives should be described in future safety assessments. This is also recommended in the general recommendations to SKI's draft regulations (see Chapter 2).

Furthermore, in the authorities' opinion, SKB should, in future safety assessments, provide a more detailed discussion of the importance of time-dependent processes. One example is that processes that could lead to an accumulation and subsequent flushing of radionuclides from the geosphere to the biosphere are not evaluated in the climate scenario.

Relevance of SKB's Scenarios for Risk Assessment

The authorities share the view of the IRT that the scenarios in SR 97 provide acceptable coverage of what can be expected to be included in a safety assessment. However, in the authorities' opinion, SKB should clarify the coupling between scenario selection and risk assessment. The authorities consider that although the weighing together of the risks in the different scenarios presented in the final chapter of SR 97 (Chapter 13) is numerically correct, SKB's scenarios do not adequately take into account essential couplings between different types of internal and external events in the different scenarios.

A more general finding, which contributes to the authorities' view that SKB should put more thought into the scenario issues, is that SKB's application of the definition of a scenario in SR 97 is not consistently applied. The canister defect scenario is, for example, not a description of the entire repository system, but only covers a small fraction of all of the canisters in the repository. The authorities therefore recommend that SKB review its method for formulating scenarios so that the scenarios provide a good basis for, and are logically connected to, the risk calculations.

4.3.6 Exposure and Exposure Pathways in the Biosphere

The most important comments in the regulatory review of SKB's modelling of the biosphere and those processes that result in a dose to man and the environment are presented here. Comments on SKB's methods for assessing health and environmental protection are provided in Section 4.3.9. Comments on SKB's description of initial states and processes in the biosphere are provided in Appendix 1, Chapter 2.

Calculation Assumptions
The account of the biosphere calculations that have been performed is not clear. It might seem that SKB's choice of peat bogs as a conservative representative of all other ecosystems renders a detailed description unnecessary. However, there are several reasons why such a simplification should not be made:

- Conservative assumptions, that is, overestimations that can justify omitting certain stages in the analysis, need to be relatively extensively justified. This means that the omitted stages still have to be described in detail.
- As mentioned in Section 4.3.9, it is too early to have goal fulfilment as the only central purpose of the analysis described. An important aim is to describe the approach and weak points of the analysis.

Consequently, the authorities consider that SKB should:

- Support the assumption made in SR 97 that the transition between the geosphere and biosphere is conservative, namely that radionuclides are assumed to move directly from the groundwater to the root zone.
- Continue its work on describing relevant ecosystems.
- Identify radionuclides that are critical for the consequence analysis.
- Develop its work on exposure pathways so that objects to be protected, other than human health, are treated in an acceptable manner, which is a condition for compliance with SSI's regulations (Chapter 2).

The position of man in the analyzed ecosystems is also unclear. In its biosphere model, SKB sometimes uses a well and sometimes uses other ecosystems. In the authorities' opinion, SKB should study the effects of combinations of exposure pathways, multiple exposure, in cases where this cannot be excluded, such as exposure via drinking water consumption combined with other potential exposure pathways. Alternatively, a more detailed reasoning must be presented to show that the description is conservative.

The fact that Aberg is under water for a large part of the time investigated has already been commented upon above. The authorities do not consider that SKB has, in a convincing manner, shown that Aberg (Äspö) could not be exposed to glaciation and yet be above the water line for a considerably longer time than specified in the climate scenario. Another issue that is relevant for any coastal siting of a repository, and should therefore have been described in the case of Aberg, is an outflow to sediments that become inaccessible to new exposure pathways due to land elevation. In this scenario, there is a specific type of risk of impact on the environment and man that is not analyzed in SR 97.

Time
The regulations (see Chapter 2) require that SKB should describe repository safety for very long time-frames. However, in the authorities' view the process has come so far that it is high time for SKB to develop all of the theoretical tools that will be subsequently needed for an ultimate licensing, including a specific description of the thousand-year time-frame that is required by the regulations (SSI, 1999). One approach is to define and discuss the scenarios (including extreme scenarios) that *could result* in an individual dose during this time. It is in the interest of the public that this shorter time-frame – from repository closure to a few hundred years in the future – should be thoroughly described.

For long time periods, doses can only be estimated for a reference society and reference biosphere. As described in Chapters 2 and 3, doses to man after very long time periods can be used as a measure of safety. SSI has stated that the present-day biosphere and society could be used as a starting point, which does not exclude the possibility of conducting additional analyses.

Role of the Biosphere in Future Analyses
In the authorities' opinion, if SKB decides to continue to placing particular emphasis on analyses based on peat bogs, SKB should present a more detailed description of exposure pathways from peat bogs to man. In a study of peat and radiation protection conducted by SSI (SSI, 1990), a waste landfill with peat ash is perhaps the greatest problem from the standpoint of radiation protection. However, this exposure pathway has not been described in SKB's background report (Lindborg and Shüldt, 1998), in spite of the fact that it is assumed, in SR 97, that peat will be used as fuel in the future. The authorities also recommend that SKB develop a model for forest ecosystems.

At the same time, it is clear that SKB cannot describe all possible biosphere scenarios for a hypothetical release. Therefore, SSI must establish more detailed criteria for the assessment of the risk. Nevetheless, since SKB has the ultimate responsibility, SKB should not passively wait for the authorities to work on this issue.

4.3.7 Development and Selection of Conceptual Models

In the IRT's opinion (SKI, 2000a), SKI has access to a suitable set of models for the needs of the safety assessment. However, the IRT and Wilmot and Crawford (SKI 2000c) state that SKB should develop a more complete and traceable documentation, for example, with respect to conceptual assumptions, the importance of simplifications and mathematical and numerical methods. The experts also maintain that SKB should be clearer in its description of how various models have been selected in the different stages of the safety assessment, from the selection of detailed process models to the selection of the more simplified calculation models for the consequence analysis.

Several of SKI's consultants as well as Pereira (SKI, 2000b) emphasize that SKB should discuss uncertainties in the models used for the calculation of radionuclide transport in the consequence analysis. These models contain major simplifications and the importance of these simplifications to the calculation results is inadequately described in SR 97. In the opinion of Wörman and Xu as well as Tsang, the uncertainties in the simplified transport models, for example, should be illustrated through comparisons with more detailed process models for different transport processes.

In the view of the authorities, SKB developed a set of suitable models before conducting SR 97. These models correspond to the level of ambition that can be expected at this stage. However, the authorities agree to a certain extent with the criticism presented above, that the description of the model limitations and uncertainties must be improved. There is an imbalance in SR 97 in this respect, where the impact of conceptual uncertainties on hydrogeological modelling is analyzed in relative detail while there is no corresponding analysis for the models of the evolution of the near field and of radionuclide transport. In the authorities' opinion, the background report "Processes in the Repository Evolution" is a laudable initiative to document the scientific understanding of the underlying processes in the models. However, in future safety assessments, SKB should be clearer in its presentation of how the process descriptions are used in the selection of conceptual models.

The authorities share the view of the IRT that the evaluation of alternative hydrological models for Aberg is a valuable example of how understanding can be created for model uncertainty. However, the authorities find that SKB has, in most cases, nevertheless selected and used a single conceptual model for the different calculations in the safety assessments. In the authorities' view, it is important for SKB to formulate a carefully prepared strategy for using and excluding alternative conceptual models, which also describes the need for measurement data for the different models, prior to starting site investigations.

4.3.8 Data Selection

In the authorities' opinion, the background report, "Data and Data Uncertainties" (where SKB's selection of data for the canister defect scenario is justified) generally provides a good discussion of the scientific basis for the selection of parameter values.

However, in the authorities' view, SKB should use well-defined procedures that have been subjected to quality assurance to select data, since it is often not clear in SR 97, how the judgements have been made and which experts have been involved (see also Section 4.3.11). The authorities also recommend that, before future licensing, SKB should supplement this background report with the required data for analyzing other scenarios besides the canister defect scenario.

The parameters discussed in this background report exclusively reflect the need for data for the often simplified models used to calculate radionuclide transport. Wörman and Xu (SKI, 2000c) emphasize that uncertainties in these models are not adequately discussed and that it is unclear how these uncertainties can affect the need for data from site investigations. Wörman and Xu therefore emphasize that the identification of important parameters must also be based on more basic process models and descriptions of relevant transport processes. Geier (SKI, 2000c) considers that SKB should improve its discussion of the possibility of obtaining relevant data in connection with the selection of a main model (HYDRASTAR) for modelling groundwater flow and transport paths.

The IRT (SKI, 2000a) and several of SKI's consultants have commented on SKB's method of selecting data for the risk calculations. In the opinion of Wilmot and Crawford (SKI, 2000c), while the use of (bimodal) distributions with a reasonable and a pessimistic value is not incorrect, the probabilities of 0.9 and 0.1 appear to be arbitrarily chosen. In the view of IRT and Pereira (SKI, 2000b), unlike SKB, the deficiencies in the data for certain parameters cannot be taken as a justification to limit the analyzed parameter intervals in the way that this has been done in SR 97.

In the view of the authorities, SKB should develop its method for data selection for the risk calculations, since SKB has not shown that the bimodal distributions, with a probability of 0.9 and 0.1 for reasonable and pessimistic values, is a conservative choice. The authorities also agree with the external reviewers that there is a measure of arbitrariness in SKB's way of representing a parameter and the related uncertainty with the bimodal distributions, which means that the analysis could be difficult to evaluate and the statistic implications would be unclear.

4.3.9 Measurement of the Protective Capability of the Repository

Health Protection

SKB has applied the concepts "dose" and "risk" correctly, as they are defined in SSI's regulations (Chapter 2). SKB has stated that since the highest dose affects a small area, it has used the annual risk of 10^{-5} as the criterion for compliance. This approach is not mentioned in the regulations but in the commentary, where it is stated: "If the proponent wishes to perform calculations with respect to an individual who is estimated to have a high dose commitment, it may be acceptable to perform the calculations for an individual who represents the higher level within the range, instead of an individual who is representative of the commitment of the entire group." (SSI, 1999). SSI uses the expression "may be acceptable" since SSI's intention is to require that the representativity of the test individual should be described.

In the view of the authorities, SKB should prepare to specifically justify the relationship between the individual or group with the highest dose commitment and the dose commitment for other larger groups. Such a description should contain a number of alternatives which are analyzed with respect to the dose distribution over a larger group. In cases with a more evenly exposed large group which can occur in connection with releases to lakes, SKB is correct to make a comparison with the stipulated limit of 10^{-6} for the annual risk.

Environmental Protection
In this context, environmental protection refers to protection against the biological effects of ionizing radiation on organisms other than man and on ecological systems (see Chapter 2). The IRT finds that these issues are not dealt with in SR 97 and that SKB refers to an unsupported assumption that the radiation effects on living environments are negligible if the releases from the repository are lower than the background radiation. However, during its review work, the IRT was informed that SKB has started development work within the area and recommends that the authorities and the industry discuss the issue further. The IRT's conclusion is that the deficiencies relating to the treatment of environmental protection do not affect the overall conclusions regarding the safety of the KBS-3 method that is presented in SR 97.

In the authorities' opinion, the description of environmental consequences provided in SR 97 falls far short of the authorities' requirements. SKB must prioritize work in this area in order to be able to produce a description that complies with regulatory requirements in connection with a future application for permission to construct a nuclear facility. The authorities find that SKB, in its new safety report for SFR, is planning to perform an ecosystem-based assessment that has a completely different development potential than that shown in SR 97 (SKB, 1998). In the authorities' view, SKB should develop this methodology and use it to assess the long-term environmental protective capability of the KBS-3 method.

Alternative Measures of Repository Performance
For the reasonable case in the canister defect scenario, SKB describes the mass flows (Bq/year) from the near and far field. Apart from this, alternative safety indicators of dose are not discussed. This is not in line with SKI's current recommendations for long time periods (exceeding 1,000 years). The results of the calculations should, if possible, be illustrated using several safety indicators to provide a comprehensive view of the risks that are associated with the repository.

When a hypothetical outflow from the repository is analyzed, the consequences can be described so that they follow the calculation results in several stages:
- Outflow from the engineered barriers in the repository, namely a measure of the quantity of radioactive substances that penetrate the different engineered barriers. These indicators are a measure of barrier performance.
- Indicators that specify an interim result in the form of outflows to the biosphere.
- Concentrations of radioactive substances in the biosphere.
- Consequences to health and the environment.

All of the calculation results above can be used as safety indicators that can serve different purposes. Dose and dose calculations serve an important purpose in that they show that safety and radiation protection requirements can be met. Another purpose could be to describe differences between different sites and the relative importance of the different barriers. In the authorities' view, alternative indicators, such as the outflow of radioactive substances to the biosphere, are better suited to this purpose.

Alternative safety indicators, such as outflows of radioactive substances from the canister and buffer, also provide important information to be able to derive performance requirements for the engineered barriers and the rock. This is particularly important for the situation at this point, when all of the repository components have not yet been determined or fully developed.

4.3.10 Risk Analysis and Calculations

Uncertainty and Sensitivity Calculations

For the canister defect scenario, SKB presents a set of calculation cases that can, in a comprehensive way, illustrate different aspects of repository performance. The calculation cases for the canister defect scenario also provide an adequate coverage of the views expressed in SKI's draft regulations (Chapter 2). The calculations reported for the remaining scenarios are closer to rough estimates and mainly serve the purpose of illustrating the minor importance of these scenarios from the standpoint of consequences. In the authorities' opinion, SKB must develop the analyses for all scenarios so that they are as extensive as those for the canister defect scenario. This view has also been put forward by the IRT (SKI, 2000a), by Voss and Tsang respectively (SKI, 2000c) as well as by Pereira (SKI, 2000b).

The uncertainty and sensitivity analysis that SKB conducts for the canister defect scenario provides a valuable insight into how the repository system can be affected by various factors. However, in the authorities' opinion, the analyses must be supplemented to describe the importance of the potentially unfavourable FEPs that have been excluded from SR 97, such as alternative assumptions regarding initial defects in canisters, damage to the buffer, oxidizing conditions etc. (see also Appendix 1, Section 1.4.1). Furthermore, in the authorities' view, SKB should develop a more systematic sensitivity analysis, in order to be able to identify parameters that are of particular importance and that must be included in the probabilistic calculations. A review of the impact of the parameters on consequences, in terms of linear and non-linear relationships, may also be necessary for this purpose.

In the authorities' opinion, SKB's approach to only vary one parameter or parameter group at a time has limited the uncertainty analyses in SR 97. The multiple parameter variations that are analytically performed for retardation in the geosphere could be developed to cover the full calculation chain. In order to clarify the importance of the selected parameter interval, SKB should also perform a sensitivity analysis that separates the effects of the model sensitivity and the width of the estimated parameter intervals. Additional views of the authorities on the uncertainty and sensitivity analyses are provided in Appendix 2, Chapter 2.

Risk Calculations
Due to the difficulties connected with systematically and stringently calculating the long-term radiological risk from a repository, as well as the uncertainties associated with the repository and the surrounding environment, it is not satisfactory to present the calculated risk alone. The proponent must also describe the calculations performed in an adequately transparent manner. The method used by SKB for the risk analysis in SR 97, is not presented in the reports. However, it is possible to derive SKB's method in part from Chapters 4, 7, 9 and 13 in SR 97.

The risk calculations performed by SKB for the canister defect scenario are presented in the form of cumulative dose distribution diagrams (cdf diagrams). These diagrams provide information on the dose distribution from the Monte-Carlo analysis that SKB has performed for the scenario by randomly varying a number of parameter values. For each calculation performed, the highest dose received has been set off in the cdf diagrams. The authorities find that SKB's approach is conservative since SKB has sampled the highest dose for each realisation, regardless of *where* and *when* the release occurrred. However, the authorities believe that, in the future, SKB should present the calculations in such a way that it is also clear how the calculated doses are distributed in time and how the doses are distributed between different exposure pathways.

The probabilistic analysis that SKB performs for the canister defect scenario is a good first attempt, although certain aspects must be improved in future safety assessments. SKB has not taken into account parameter correlations, except for near field flows and transit times. In SR 97, SKB admits that this is so, but considers that this is a conservative approach. The authorities consider that this issue merits further investigation since it cannot be excluded that there may be combinations of unfavourable conditions that can lead to a deterioration in repository performance, which is also emphasized in SKI's safety assessment, SITE-94 (SKI, 1996b).

The IRT (SKI, 2000a), Wilmot and Crawford (SKI, 2000c) and Pereira (SKI, 2000b) question SKB's conclusion that the form of the estimated dose calculations provides an indication of repository robustness, with respect to SKB's way of representing data uncertainties with reasonable and pessimistic values. In its statement of July 7, 2000 (SKI, 2000b), concerning the opinions of the reviewing bodies on SR 97, SKB states that the form of the assumed data distributions (bimodal distribution) is of minor importance as long as the mean value and variance do not change. SKB also states that it intends to confirm this with further analyses after the review of SR 97.

The authorities agree with the consultants that SKB's way of representing uncertainties in input data is not clear and that it cannot be considered to be evident, in the way that SKB maintains, that the radiological risk has been overestimated through the approach that SKB has taken. The authorities assume that SKB will review the representation of uncertainties in data in connection with the planned evaluation of the method for probabilistic risk calculations.

The risk calculations are directly linked to the selection of calculation cases and scenarios. In the final evaluation of risk, the risk contribution from the different calculation cases must be aggregated. This aggregation must take into account the probability of the scenarios that contribute to risk. As a matter of principle, these probabilities should be standardized. In the authorities' view, the balancing of risk contributions from the scenarios selected in SR 97 has been performed in a conservative manner. However, SKB's reasoning is based on the fact that a single scenario, the canister defect scenario, is estimated to dominate the expected future doses. In the authorities' opinion, SKB should, prior to future safety assessments, develop a more general method for the total risk assessment that can handle a situation with significant risk contributions from more than one scenario.

4.3.11 Documentation of Expert Judgement

A safety assessment of a repository for spent nuclear fuel will always be associated with uncertainties and deficiencies in the knowledge base. These must be handled by using expert judgement of various types. In this context, expert judgement means the choice, based on available knowledge, of models, data and other premises for the safety assessment. For the authorities to evaluate the credibility of the safety assessment, it is essential that all expert judgements should be well documented, performed in a traceable manner and based on established scientific fact.

The authorities consider that SKB has made considerable progress in SR 97 with respect to describing the assumptions used for the safety assessment through the systematic review of processes and input data for the consequence calculations presented in the background report, "Processes in the Repository Evolution". However, in the authorities' opinion, SKB would benefit from using well-defined procedures that have been subjected to quality assurance, primarily for the documentation but also for the implementation of expert judgements, in order to improve traceability and to facilitate the regulatory review work.

The authorities share the view of the IRT (SKI, 2000a) and of several of SKI's consultants (SKI, 2000c) that there are deficiencies in SR 97 with respect to the reporting of the criteria that have been used for various types of judgements, the individuals or organizations that are responsible for the judgements and the way in which the judgements have been made. Examples of areas where SKB should reinforce the documentation of the expert judgements are:

- scenario selection
- the selection of FEPs that have been included or excluded from the safety assessment, such as the occurrence of oxygenated conditions at repository depth and colloidal transport of radionuclides
- the selection of models and other premises for calculation, such as assumptions concerning (initial) defects in the canister and buffer and models for the corrosion of initially defective canisters
- the selection of difficult-to-determine parameter values in the "Data and Data Uncertainties" report, such as the flow wetted surface area and distribution coefficients.

In cases where the knowledge base for important judgements is deficient, SKB should consider some form of independent peer review. Another possibility is to arrange formal expert elicitation, as proposed by Wilmot and Crawford and Tsang, respectively. The

IRT's work, which was carried out for SR 97, is an example of an independent peer review. However, it cannot be expected that such a review will evaluate all parts of the comprehensive safety assessment in depth. In the authorities' view, prior to future licensing, SKB should to a greater extent, evaluate the quality and completeness of the most important data and assumptions, even before the safety assessment is completed.

4.3.12 Basis for Deriving Requirements for Site Investigation Programmes and Performance Requirements for Engineered Barriers

Feedback to Site Selection and Site Investigations

One aim of SR 97 is to provide a basis for specifying the factors upon which the selection of areas for site investigations is based and for deriving the parameters that must be determined in a site investigation. In the final chapter, SKB states that the results of SR 97 have been used in work on formulating requirements and preferences for the rock. This work is being conducted in parallel with SR 97. SKB also states that SR 97 has been used to define preferences for value ranges for various geoscientific parameters. Apart from this, no detailed discussion is presented on the significance of the safety assessment for the site investigation programme.

The IRT (SKI, 2000a) does not consider that SR 97 fulfils the purpose of providing a basis for the optimization of site investigation programmes and repository design. The reason is that the uncertainty and sensitivity analyses are too limited and focused on showing that the requirements on safety and radiation protection can be fulfilled. Furthermore, the use of simplified models and pessimistic assumptions has meant that it has not been possible to adequately determine the importance of differences in the properties and evolution of the sites. At the same time, the IRT considers that SKB has adequate experience from site investigations at Äspö and other locations and that this can be used to develop the site investigation programme.

Voss (SKI, 2000c) and KASAM (SKI, 2000b) express similar views. In their view, SKB has not adequately highlighted the safety-related importance of the site-specific differences that have actually been identified in SR 97. Voss also considers that the assumptions regarding the performance of the near field (intact bentonite buffer and assumptions concerning canister defects) are optimistic and that this means that it has not been possible to test the rock's safety-related importance for the transport of radionuclides in a meaningful way. Therefore, SR 97, does not provide sufficient information concerning what should be measured in a site investigation.

The authorities share the opinion of the IRT that SKB has extensive experience from site investigations at Äspö which can be used to develop the site investigation programme. The authorities also consider that SR 97 has provided a valuable basis for SKB's further work on site selection and site investigations. However, the authorities agree on the whole with the criticism from the IRT and SKI's consultants and, therefore, reiterate SKI's recommendation from previous reviews of SKB's RD&D programmes, namely that SKB should develop the safety assessment and continue its work on the evaluations that are necessary for clearer feedback to the work that SKB is conducting on site investigations and on repository design.

SKB concludes, based on the results presented in the canister defect scenario, that a repository at all three sites (Aberg, Beberg and Ceberg) would have good prospects of meeting SSI's radiation protection criteria. However, the risk calculations show significant site-specific differences, with smaller margins for Aberg than for Beberg and Ceberg. Furthermore, as is stated by the consultants above, these differences could have been considerably greater with other (more pessimistic) assumptions concerning near field performance. Therefore, the authorities consider that site-specific differences in the geological conditions must still be accorded considerable importance in the selection of repository sites.

The development of the site investigation programme and the specification of site selection factors are being conducted by SKB in separate projects. In the authorities' opinion, it is important that SKB, prior to the start of the site investigations, should clearly describe how the experience from SR 97, including the views put forward in this review report, have been incorporated into this work. The authorities intend to return to the evaluation of SKB's programme for site investigations in connection with the evaluation of RD&D 98 Supplement and RD&D 01.

Feedback to the Development Work on the Engineered Barriers

In SR 97, SKB states that the results from the safety assessment will be used as a basis for a review of the performance requirements and design basis requirements that will determine the design of the canister and the other engineered barriers. However, SKB states that only in a few cases can the performance requirements be directly derived from the analysis results.

The authorities understand this objection. However, in the authorities' opinion, this is partly a result of the limited sensitivity and uncertainty analyses in SR 97. On the basis of more systematic analyses of how various types of initial defects in the canister and buffer will develop in the repository, it should be possible to detail both the design requirements on the engineered barriers and requirements on control methods for manufacturing, closure and handling. In the authorities' view, it is essential that SKB, in its future work, should improve its description of how performance and safety assessments are used to ensure the feedback to the development work on the engineered barriers.

5 SKI and SSI's Overall Evaluation

5.1 Introduction

This chapter summarizes the authorities' evaluation of the technical premises for the safety assessment (Section 5.2) and how SR 97 fulfils the purposes of:

- Demonstrating safety assessment methodology, including system description, scenario and calculation case selection, treatment of uncertainties, measures of the repository protective capability, methods for risk analysis, structure and presentation (Section 5.3).
- Showing that KBS-3 would have good prospects of meeting long-term safety and radiation protection requirements and to demonstrate the feasibility of finding a site in Sweden that meets the requirements (Section 5.4).
- Providing material for site selection and the development work on the site investigation and engineered barrier programmes (Section 5.5).

The premises for evaluating the extent to which these purposes have been fulfilled are described in greater detail in Section 2.4, where it is stated that the methodology, technical data and consequence analysis should be taken into account in the evaluation of safety and radiation protection. The consequence analysis is examined here together with the methodology issue in Section 5.3. As has been explained in Chapter 2, it is not reasonable, at this stage, to strictly apply the regulations in the evaluation of the safety assessment methods and in the evaluation of the overall requirements on safety and radiation protection. On the other hand, the authorities have investigated whether or not, based on the information presented by SKB in SR 97, there may be any unresolved issue that is so serious that it would mean that the construction of a repository in accordance with the KBS-3 method would not comply the safety and radiation protection requirements. The authorities' findings are presented in Section 5.4.

It should be emphasized that, at the current stage of SKB's work on the development of the KBS system, certain parts of a safety assessment must be based on assumptions made on the basis of present-day knowledge. This primarily concerns the operation of the repository including barrier manufacturing. Furthermore, data are not yet available from repository candidate site investigations. SKB is currently conducting extensive work to develop the engineered barriers and final disposal technology. The regulatory review of SR 97 does not include an evaluation of this work. The main review of such work will be carried out in connection with the review of SKB's recurrent RD&D programme reports.

In the forthcoming regulatory review of SKB's programme (including the RD&D Programme 98 Supplement), the authorities can, under the Act on Nuclear Activities, propose to the Government requirements that should be made on SKB's further work. These proposals will be based on the review of SR 97 and on the supplementary information requested by the Government, including a supplementary analysis of alternatives to the KBS-3 method, an overall evaluation of feasibility studies and other information which will be used as a basis for site selection as well as a programme for site investigations. The regulatory review of SR 97 should be considered in the light of this larger context. Therefore, no proposals are provided in this review report regarding formal requirements to be made on SKB.

5.2 Data and Technical Premises for the Safety Assessment

The assumptions concerning the initial state of the engineered barriers are essential premises for the analyses presented in SR 97. In practice, SKB's assumption is that one of the canisters is deposited with an initial defect while the other canisters are intact at the time of deposition. Furthermore, in SR 97, it is assumed that the buffer is intact and that the evolution of the buffer surrounding each canister is the similar. Issues relating to the long-term evolution of the backfill and plugs are not dealt within SR 97.

Bearing in mind the fact that knowledge of the engineered barriers is incomplete and that there is a need to provide feedback to the development work on the engineered barriers, the authorities' opinion is that alternative types of canister damage and damage frequencies should have been more fully developed in SR 97. For the same reason, the authorities consider that SKB, in future safety assessments, should assess the importance of malfunctions of the buffer, backfill and plugs, particularly with respect to thermal effects during buffer resaturation.

In SR 97, SKB has used data from three previously investigated sites: Äspö (Aberg), Finnsjön (Beberg) and Gideå (Ceberg). Although the site data vary in scope and quality, depending on the site, the authorities consider the scope of the data to be reasonable in relation to the purposes of SR 97. Furthermore, in the authorities' opinion, the data provide a reasonable coverage of the conditions that can be expected at the sites that are being considered for SKB's planned site investigations. The biosphere modelling is based on the existing ecosystems at the three sites.

5.3 Demonstrate Safety Assessment Methodology

In the opinion of the authorities, SKB has demonstrated in SR 97 that it has access to qualified scientific data and the necessary tools and methods to assess the long-term safety of a repository for spent nuclear fuel. The safety assessment methodology presented in SR 97 has been developed, in several respects, in relation to previously presented safety assessments. For example, in SR 97, SKB has taken a first step to adapting its safety reports to the requirements of the authorities' regulations, including the presentation of the protective capability of the repository in terms of risk. The methodology of SR 97 also qualitatively meets the requirements on scope and content specified in SKI's draft regulations on safety in connection with final disposal (see Chapter 2) and, thereby, is a sound platform for SKB's further safety assessment development work.

At the same time, in their review, the authorities find that some parts of the methodology presented in SR 97 must be further developed and detailed prior to future licensing, as described below. Essential aspects of the criticism provided in this review have been communicated earlier, such as in connection with SKI's review of SKB's SKB 91 performance assessment (SKI, 1992). In the authorities' opinion, some of the deficiencies found could have been avoided if SKB had, to a greater extent, taken into account in SR 97 the premises for the safety assessment that SKB itself formulated in SR 95 (SKB, 1995). Examples include the discussions on completeness in connection with scenario selection, model validation and the evaluation of calculation results, taking into account various types of uncertainties.

Structure and Presentation
In the authorities' opinion, SR 97 is on the whole well-written and organized. SR 97 contains the components that, according to SKI's draft regulations concerning safety in connection with the final disposal of nuclear waste, should be included in a safety report. The main criticism of the presentation of information in SR 97 relates to deficiencies in traceability and transparency with respect to different types of judgements made as well as deficiencies in documentation with respect to parts of the safety assessment methodology, such as scenario selection and risk analysis. Furthermore, the description of biosphere processes and biosphere models is inadequate in the SR 97 Main Report and background reports. All essential information must be taken from sub-references. However, in the authorities' opinion, these issues can be dealt with in SKB's ongoing work on developing a basic structure for safety reports.

Focus of the Safety Assessment
SKB states that, in SR 97, it has placed greater emphasis on analyses of the isolating functions of the repository, compared with previous safety assessments. In the opinion of the authorities, this should have led to a more in-depth analysis of the uncertainties associated with the engineered barriers and their evolution in the repository, particularly with regard to possible defects in and malfunctions of the canister and buffer as well as the importance of long-term chemical changes in the buffer. Such an evaluation of uncertainties is valuable in order to assess the barrier performance of the rock and in order to formulate performance requirements for the engineered barriers. These views have previously been expressed, for example in SKI's review of SKB's SKB 91 performance assessment (SKI, 1992).

System Description
In the authorities' opinion, the newly developed THMC diagrams are a good complement to previously developed methods for system description and for the visualization of processes in the repository. However, SKB should develop the method in order to improve the inclusion of time-dependent effects and structural changes. SKB should also continue its work on developing a systematic description of the processes in the biosphere.

SR 97 contains a systematic review of the processes and data used in the consequence analysis for the canister defect scenario. Although this documentation represents a major step, SKB should develop the methodology, mainly in view of supporting the reasons for eliminating unfavourable processes from the consequence analysis. Alternatively, these processes should be included in the calculations so that the risk contributions can be evaluated. Colloidal transport of radionuclides and the impact of microbes on canister corrosion are two examples of such processes that have been identified in this review.

Scenarios
In the authorities' opinion, the scenarios analyzed in SR 97 provide an acceptable coverage of the internal and external events that could affect the protective capability of the repository. However, in future scenario work, SKB should ensure that these provide a good basis for, and are logically coupled to, both the system description and the risk calculations. One deficiency of SR 97 is that couplings between different events are not adequately analyzed. For example, SKB has not adequately investigated the impact that future climate changes could have on the engineered barriers, on radionuclide transport as well as on how the frequency and magnitude of earthquakes can affect the protective capability of the repository. In the authorities' view, SKB should consider analyzing more comprehensive scenarios that, in a more integrated manner, handle events and processes that can affect repository safety. SKB should also conduct a more extensive analysis of scenario uncertainties, such as climate evolution alternatives and alternative assumptions on defects in the engineered barriers.

Data and Models
In the authorities' opinion, prior to conducting SR 97, SKB developed a comprehensive set of models for the needs of the safety assessment. However, the documentation and the justification of models must be improved in future safety assessments. The evaluation of alternative hydrogeological models in SR 97 is a valuable initiative for understanding model limitations and conceptual uncertainties. A similar approach should also be considered for other parts of the model chain, such as the evolution of the near field and radionuclide transport.

It is positive that SKB is attempting to gain an understanding of the complex processes that affect the evolution of defective canisters in the repository. However, the authorities consider that the models used in SR 97 must be evaluated and better supported by data prior to future safety assessments. The corrosion analysis for intact canisters must be better validated against experiments and other corrosion models. Furthermore, SKB should take the canister weld joints into account in the corrosion analysis.

With respect to the selection of data, the authorities consider that the background report, "Data and Data Uncertainties" is a laudable initiative, even if data used in other contexts besides the consequence analysis for the canister defect scenario should have been documented in a similar manner.

In SR 97, SKB has taken a first step towards a more structured biosphere modelling by analyzing a number of exposure pathways in different ecosystems for the hypothetical repository sites, Aberg, Beberg and Ceberg. However, in the authorities' opinion, SKB should improve its understanding of radionuclide migration from the geosphere to the biosphere and develop its assessment of environmental protection in order to comply with the regulatory requirements. SKB should also take into account the possibility that several exposure pathways can lead to simultaneous exposure. For example, exposure via drinking water consumption must be studied together with other possible exposure pathways.

Measures of the Protective Capability of the Repository

In the authorities' opinion, SKB has correctly interpreted SSI's health protection requirements in the SSI FS 1998:1 regulations (SSI, 1999), which stipulate that the risk limit for large populations is 10^{-6} per year. In the authorities' view, SKB should justify, in greater detail, its selection of the individual or group with the highest dose commitment, since it is not clear how this individual/group stands in relation to a larger population.

The assessment of environmental protection in SR 97 is deficient. However, the authorities are aware that SKB is actively working on this issue. The authorities are expecting that SKB will initiate further work within this area, as is reflected in SSI's regulations (SSI, 1999).

SKB states that it did not take into account the dilution of radioactive substances and migration in the biosphere as a safety function, with the explanation that it is difficult to predict the evolution of the biosphere. At the same time, dilution in the biosphere is a deciding factor in the assessment of the consequences of the climate scenario. In the view of the authorities, SKB should, in consultation with the authorities, define the role of the biosphere prior to future safety assessments.

SKB has only, to a limited extent, used alternative measures of the repository protective capability. In the authorities' view, alternative safety indicators, such as the flow of radionuclides from the geosphere to the biosphere, and radionuclide concentration in the environment, are essential complements to dose and risk and can be used to obtain information on differences between repository sites. A discussion on the results for Aberg with respect to alternative safety indicators would have been valuable.

Risk Analyses and Calculations

In the opinion of the authorities, in its canister defect scenario, SKB has developed a set of calculation cases that describe the interactions of the various barrier functions and illustrate the possible consequences of leakage from a defect canister. However, it should be possible to considerably develop the uncertainty and sensitivity analyses for example by including variations of more than one parameter or parameter group at a time as well as hypothetical examples that more stringently test individual barrier functions.

In the authorities' opinion, the risk calculations in SR 97 are a first step in adapting to the use of a risk criterion. However, SKB should develop a less arbitrary method of representing probabilities for the many parameters that are included in the risk analysis. Correlations between different parameters in the risk analysis should also be studied in greater detail, since these could have a considerable impact on the final result. In the view of the authorities, a specific account of the protective capability of the repository in the short term (0 – 1,000 years after closure), as stipulated in SSI's regulations on the final management of nuclear waste, is also lacking.

Expert Judgement

In the authorities' opinion, SR 97 provides a good review and description of the processes that can affect repository performance and of the data used to calculate radionuclide transport in the canister defect scenario. However, prior to future safety assessments for licence applications, SKB should develop procedures for the documentation and implementation of the expert judgements used to select models, data and other premises for the safety assessment that are well defined and that have been subjected to quality assurance. The authorities would also like to recommend that SKB subject the most important data and assumptions to independent peer review before the safety assessment is completed.

5.4 Compliance with Safety and Radiation Protection Requirements

One overall purpose of SR 97 is to demonstrate that KBS-3 has good prospects of meeting the long-term safety and radiation protection requirements and to show that it is possible to find a site in Sweden that meets the requirements. In SR 97, SKB states that: "a safe deep repository for spent nuclear fuel, based on the KBS-3 method, can be constructed at a site with conditions similar to those exemplified in the three examples – Aberg, Beberg and Ceberg".

In their review of SR 97, SKI and SSI have not found any obstacles to prevent geological final disposal in accordance with the KBS-3 method from meeting the required safety and radiation protection requirements. Based on the review of SR 97 and the previous review of SKB's RD&D programme, the authorities consider that the KBS-3 method is a good basis for SKB's future site investigations and the further development of the engineered barriers. However, a detailed evaluation of the prospects of the KBS-3 method in meeting the requirements can only be made once detailed data have been obtained from the site investigations and when more extensive practical experience concerning manufacturing and testing the engineered barriers has been gained. Furthermore, SKB must supplement and develop its safety assessment methods, taking into account the findings of the regulatory review of SR 97.

5.5 SR 97 as a Basis for Site Investigations and Function Requirements

SR 97 must also provide a basis for deriving the parameters to be measured in a site investigation and for specifying the factors for selecting sites for investigation. Furthermore, SR 97 must provide a basis for deriving preliminary function requirements with respect to the engineered barriers.

In the authorities' opinion, SR 97 has provided SKB with a basis for further work on the site investigation and function requirements. However, the authorities find that SR 97 does not contain any in-depth discussion of what the results of the safety assessment would mean for the site investigation programme and the function requirements for the engineered barriers. Instead, SKB states that the results from SR 97 will be dealt with in separate projects, including the project to develop the site investigation programme, the formulation of requirements and preferences with respect to the bedrock and the review of functional requirements and design basis requirements for the canister and the other barriers. Therefore, the authorities intend to return to these issues in connection with the regulatory review of SKB's supplement to RD&D Programme 98 and, at a later stage, in connection with the review of SKB's RD&D Programme 01.

In this review, the authorities have stated that SKB should conduct more comprehensive analyses of uncertainties in the assumptions used for the canister and buffer performance in order to better determine the importance of the rock barrier to safety and to thereby identify which parameters it is important to study in a site investigation. In the authorities' view, such analyses are also necessary for SKB to specify design requirements for the engineered barriers. It is important for SKB to evaluate the experience from SR 97, including the findings of the regulatory review, in its further development work on the site investigation programme and the engineered barriers.

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APPENDIX 1

1 Processes and Initial State of the Engineered Barriers and Geosphere

1.1 Introduction

SKB divides the safety assessment into five different stages: the system description, description of initial state, scenario selection, analysis of selected scenarios and evaluation. The regulatory review of the description of the system and the initial states are presented in this chapter. The review primarily concerns Chapter 5 as well as Sections 4.2 and 6.1-5 in the Main Report as well as relevant descriptions in the background report, "Processes in the Repository Evolution".

SKB has described the method used in SR 97 to describe properties and processes determining the evolution of the repository ("the process system") in the report "Identification and Structuring of Processes" (Pers et al., 1999). An overview of the methodology used is also provided in Chapter 4 of the Main Report.

1.2 SKB's Report

System Description – THMC Diagrams
A systematic method must be used to identify and describe features, events and processes (FEPs) that affect repository performance. SKB and SKI both hold a prominent position among those organizations which, in the last ten years, have developed methods for this purpose.

SKB previously developed and used interaction matrices to identify the processes in the repository. However, this type of identification was conducted independently from the rest of the safety assessment and it was difficult to integrate. Therefore, in SR 97, SKB developed and tested a new structure for system description, in the form of THMC diagrams. The main features of this method are:

- the repository is divided up into four subsystems, each corresponding to the barriers in the KBS-3 method: the fuel, canister, buffer (including backfill) and rock;
- a table, including relevant processes classified as Thermal (T), Hydraulic (H), Mechanical (M) and Chemical (C), is created for each subsystem;
- the variables that characterize the state of the barriers and gas and liquid flows are also included in the table (see for example, Figure 4-3 in the Main Report);
- Finally, the variables and processes that affect each other are marked in the diagram.

The aim of the THMC diagrams is to clarify the processes that are active in different subsystems and how they affect the performance of the barriers. This systematic approach facilitates the identification of processes and has been used by SKB in "Processes in the Repository Evolution" and in Chapter 5 of the Main Report (System Description; Processes and Variables).

Fuel

In SR 97, all canisters are assumed, in simplified terms, to contain BWR fuel of the SVEA 96 type, with a burnup of 38 MWd/tU. This fuel has been used as a premise for the radionuclide inventory used in the consequence analysis. SKB identifies the processes and variables that affect the state of the fuel and the cavity inside the canister. The most important of these processes are radioactive decay, radiation effects, heat generation, heat transport and chemical processes which, in turn, affect water chemistry and gas generation.

Canister

The canister consists of an insert of cast iron, which provides mechanical stability, and an outer shell of copper, which protects against corrosion. The copper shell is 5 cm thick and the shape of the canister is a 4.8 m high cylinder with a diameter of 1.05 m. The total weight of the canister is about 25 tonnes and it is filled with 12 BWR assemblies. A canister holds about two tonnes of fuel. The insert and canister can undergo mechanical deformation caused by external loads. This can also occur if the copper shell is breached due to the mechanical pressure of corrosion products that can form when the iron insert corrodes. However, the most important chemical process is the corrosion of the copper shell since this process in itself could jeopardize the isolating function of the canisters.

Buffer and Backfill

The function of the buffer is to provide a diffusion barrier and mechanical protection between the canister and rock, while the function of the backfill, besides limiting the flow in the tunnel system, is to prevent the buffer from penetrating into the tunnel as a result of swelling.

The functional requirements, variables and long-term safety criteria identified by SKB with respect to the buffer and backfill relate to hydraulic conductivity, density and swelling pressure. SKB also lists a number of processes (water and gas transport, thermal expansion, erosion, radiolysis etc.) that affect the performance of the buffer and are, therefore, of importance for the long-term safety of the repository.

Geosphere with Site Investigations

The description of the initial state of the geosphere in SR 97 is based on interpretations of observations at three hypothetical repository sites Aberg, Beberg and Ceberg which correspond to Äspö, Finnsjön and Gideå. In SR 97, data from these sites have been analyzed to illustrate the conditions and variables in Swedish crystalline bedrock.

1.3 Comments by the Reviewing Bodies

Fuel

In Tord Jonsson’s opinion (SKI, 2000b), more detailed calculations must be performed of the inventory of actinides in the fuel, especially to verify the existing, more general calculations where average values of flow, enrichment and burnup are used.

Canister

The National Council on Nuclear Waste (KASAM) states that cracks penetrating the copper shell and the weld joints as a result of creep should be investigated in future work. Therefore, KASAM recommends further long-term experiments in order to determine whether or not the corrosion resistance and creep ductility are adequate for the weld joints.

Bentonite Buffer and Backfill

KASAM states that a naturally occurring clay mineral such as bentonite always shows a certain inhomogeneity with respect to composition and structure. This can result in local variations in the bentonite properties. Variations can also occur when the deposition process takes place over several decades. Furthermore, KASAM would like to see a more detailed discussion of how chemical conditions affect the properties of the buffer clay. KASAM also emphasizes that the importance of the temperature gradient over the buffer during the first hundred years has probably been underestimated and that the sorption of the water and hydratized ions between the layers in the clay particles are temperature-dependent.

Geosphere

KASAM points out that SKB has not reported any site-specific rock-mechanical model studies and that SKB's assessment of the importance of the geosphere to radionuclide isolation is unclear. SKB maintains that a safe repository can be constructed on sites corresponding to Aberg, Beberg and Ceberg yet, at the same time, SKB identifies significant differences between the sites. Since there is a predominant emphasis on barriers other than the rock, especially the canister and bentonite buffer, it is difficult to evaluate the importance of the choice of different sites.

The Geological Survey of Sweden (SGU) states that an important premise for the scenarios used in SR 97 and the preliminary safety assessment for SFL3-5 (SKB, 1999) is the geological conditions at the three sites – Aberg, Beberg and Ceberg. In SGU's view, the safety assessment is far too hypothetical and a definitive safety assessment can only be conducted when data have been obtained from the site or sites that are evaluated to have good prospects for hosting a deep repository.

In SGU's opinion, SR 97 lacks an in-depth analysis of the limited geological and hydrological variations (all sites are located below the highest shoreline) that SKB describes in the report. It is not clear whether the variations are due to different rock types or the different tectonic histories of each area and thereby different fracture or fracture zone frequencies. In SGU's view, in order to clarify this, it would have been more suitable to select sites with a greater distribution of geological and hydrological conditions.

SGU would like to see a summary and analysis of available geological and hydrogeological data that could provide important information on the rock type and/or tectonic environment that generally can be considered to be most favourable to a deep repository.

Mörner of Stockholm University does not agree with SKB that new rock movements often follow already existing fracture zones. In Mörner's view, it is the rule rather than the exception that a fault follows an old line and then suddenly intersects a new line at an angle from the old line before disappearing. Mörner gives the example of the repository geometries that SKB describes for each site where the described structures have gradually grown through the one ancillary network becoming attached to the other. In Mörner's view, this process is not complete. Therefore, proposals to locate deposition tunnels next to and between fracture zones are unsuitable.

1.4 SKI and SSI's Review and Evaluation

1.4.1 System Description Methodology

THMC Diagrams

As already stated above, SKB has made a prominent contribution to the development of methods for the systematic description of the processes in a repository. However, this matter is given cursory treatment in SR 97. A retrospective and description of different alternatives would have been of value in improving the justification of the approach chosen for SR 97. Without such a background and a better justification, the use of THMC diagrams is too abstract and difficult to interpret. The possibility of classifying the processes in a deep repository into the categories of T, H, M and C were discussed in a joint project conducted by SKI and SKB concerning scenario development (Andersson et al., 1989).

When evaluating a method for system description, its main purpose should be the prime basis of the evaluation: to document the completeness of the system description. This main purpose also means that the system descriptions should be able to function as an effective tool in the review process. A more elementary purpose is that the method should also serve as a tool in the actual analysis work. However, it is important to reiterate that a good method of documenting the completeness does not necessarily imply an inherent quality assurance of the entire safety assessment. In order to achieve this aim, there must be traceability of data and models used in the safety assessment in addition to the reporting the scientific and technical data used. In both of these respects, the THMC method, on its own, does not fulfil any function and this has probably not been SKB's intention in any case.

The International Review Team (IRT) (SKI, 2000a), states that the THMC diagrams can be considered to provide a fairly simplified view of the processes in different barriers, possibly concealing many subjective judgements. However, this also applies to other methods. Furthermore, in the IRT's view, the relationship between the choice of scenarios and the use of the THMC diagrams should be developed. The opinion that the THMC diagrams are based, to a large extent, on subjective expert judgements is also expressed by Wilmot and Crawford (SKI, 2000c) who emphasize that such expert judgements must be documented.

Tsang (SKI, 2000c) largely discusses deficiencies in the choice of processes and variables that make it difficult to trace certain relationships, especially those that involve changes in structure and geometry, as well as couplings between more than two processes. Furthermore, in Tsang's view, the system analysis work should be conducted completely separately from the calculation models development and consequence analysis work.

The methods used for system description (in addition to THMC, primarily influence diagrams and interaction matrices) are all complex to understand and their use in rationalizing the safety assessment has not yet been fully demonstrated. However, in the latter respect, SR 97 is a major step. Therefore, in the authorities' view, it is important for SKB to continue the development of these methods, especially so that the methods can be of greater assistance during the review of safety assessments.

Considerable work still remains to be done before a method is developed that is superior to the others in this respect. The THMC diagrams highlight certain aspects well, partly because the diagrams can be arranged so that they closely agree with the models or logic of the analysis. For the same reason, it is also an advantage that the diagrams classify the processes into different categories, namely THMC. Many of the disadvantages of the THMC diagrams that have been pointed out by the IRT and SKI's consultants are also shared by the other available methods. The most prominent deficiency of the THMC method is that certain relationships are not immediately evident from the diagrams. However, it is also difficult to determine whether there is a better alternative in this respect.

In conclusion, the authorities view the THMC method as a valuable contribution to the safety assessment methodology although the method is not fully developed. However, there are many factors that indicate that there are still good grounds for using different methods within the same programme to study the system descriptions from different aspects. The authorities share the opinion of the consultants that the expert judgements upon which the diagrams are based must be documented. The authorities emphasize that this does not exclude the necessity of independent peer review in future review work.

Formulation of Scenarios

Lists of possible features, events and processes (FEPs, see above) are available from a number of organizations that have performed safety assessments. An international FEP database is also available which has been developed under the auspices of the NEA. In previous work, SKB has prepared a comprehensive list of these FEPs. The FEP list can be screened to eliminate FEPs that are irrelevant, from the standpoint of the geology and repository design concerned etc. The list can also be reduced in order to limit the analysis to only those FEPs that can have a significant impact on the repository system or to those that are not considered to have a low probability of occurrence. In the authorities' view, this process of elimination is inadequately described in SR 97 – one obvious example being rock erosion. The remaining FEPs are used as a basis for the system description (as described above). Another step is to formulate, on the basis of the reduced FEP list, a number of scenarios that include these FEPs. This step is not clearly presented in SR 97.

The authorities find that several potentially unfavourable FEPs have been excluded from the risk analysis in SR 97 for more or less justifiable reasons, including the justification that they are improbable. Examples of such FEPs include:

- resaturation of the buffer

- damage to the bentonite buffer (due to initial defects, erosion occurring at low salinity etc.)
- alternative types of canister defects
- oxidizing conditions in connection with glaciations
- accumulated and time-dependent effects of repeated glaciations (such as accumulation and subsequent flushing of radionuclides from the geosphere and recurrent minor rock movements in connection with glacial loading-unloading)
- long-term erosion of the geosphere
- colloidal transport of radionuclides
- effects of degradation of bolts and plugs etc.

On the other hand, SKB includes potentially favourable FEPs, even if they are uncertain. One such example is the contribution of the biosphere to safety in the climate scenario.

In the authorities' opinion, the judgements upon which the elimination of FEPs is based should be justified more adequately, namely on the basis of well-documented peer reviews and references to scientific literature (see Section 4.3.11). Another approach would be to include calculations in the risk analysis so that the risk contributions can be evaluated.

1.4.2 Fuel

In SR 97, radionuclide inventories, residual heat and radiation data for spent nuclear fuel have been obtained on the basis of ORIGEN type calculations. SKI's consultant, Grambow (SKI, 2000c) points out that this type of calculation has not been validated for certain radionuclides, such as C1-36, Se-79 and Sn-126. Consequently, the uncertainties for these radionuclides may be significant. In SR 97, the inventory of C1-36 is significantly lower than the estimates used in previously performed international projects. This difference is of particular significance for the consequence calculations, since the inventory of such a soluble radionuclide as C1-36 has a direct effect on the dose. In order to be able to evaluate certain underlying calculation results it would have been useful if SKB had divided the radionuclide inventories into fuel, cladding and metal components.

Effects of non-radioactive fission products such as xenon should have been described in greater detail since they can be of both positive and negative importance to safety.

1.4.3 Canister

Thermal Processes
In the authorities' opinion, the description of heat transport is an example of how certain relationships are not clear with the method that SKB has used for system description. The obvious relationship that heat transport in the rock determines the canister surface temperature is described in the section on heat transport in the rock ("Processes in the Repository Evolution", Section 5.4.1), but is not clear from the description of heat transport in the canister.

SKB states that a considerable uncertainty in the temperature calculations is the heat transfer over an initial gap between the copper surface and the buffer in the deposition hole. These uncertainties primarily stem from the uncertainties relating to the saturation process in the bentonite and from those relating to the emissivity of the copper. The authorities consider that a more detailed study of the significance of the surface properties for heat transfer is necessary in order to formulate design requirements for the surfaces, both with respect to machining and the storage of canisters prior to deposition. Along with the experience of surface properties gained from canister manufacturing, it should be possible to reduce the uncertainty relating to emissivity. SKB has identified the hydromechanical evolution in the gap between the canister and buffer as an area for future work and the authorities agree with this view.

Mechanical Processes

The authorities agree with SKB that the probability of a canister defect is greatest in the canister lid weld. Since no experience has yet been gained from series manufacturing of canisters, it is reasonable to assume an initial lid defect in SR 97.

SKB states that the design requirement for initial defects is that no more than 0.1% of the canisters may have defects that exceed the acceptance criteria for non-destructive testing. However, in the authorities' view, it is up to SKB to show that this is an adequate and realistic goal.

In the model study of how stresses and strains in the copper canister are formed, SKB assumes full pressure buildup after one hour. In the authorities' view, the effect of this simplification on how the results of the study are used in the case in question (where the bentonite takes up water and swells over a probable time-scale of several years) should be described more clearly.

Chemical Processes - Corrosion

SKB states that tensile stresses cannot occur to such an extent that stress corrosion would lead to a penetrating crack in the canister, since the canister is under external compression. Simple strength calculations that SKI has performed show that, under normal conditions, parts of the copper canister will be subjected to tensile stresses even if compressive stresses occur in most of the canister surface. Therefore, in the authorities' view, SKB should more clearly show that the conditions mean that stress corrosion cannot occur in the copper shell. Alternatively, SKB should take into account possible effects of stress corrosion in its analysis of the canister lifetime.

In its review of SKB's RD&D Programme 98, SKI stated that SKB should prepare a new account of how different types of corrosion provide the basis for the copper canister design, especially bearing in mind the work that is in progress and that has been conducted in the corrosion area by SKB in recent years. This update of the knowledge base would also be useful in the safety assessment.

Furthermore, in the authorities' opinion, corrosion in the cast iron insert must be studied further. SKI's consultants, Arthur and Zhou (SKI, 2000c) point out that other corrosion products besides magnetite, such as siderite and pyrite, could be formed. Experiments where corrosion products are investigated should be of value, and should provide support for SKB's opinion that the corrosion rate is determined by the transport properties of the magnetite layer. The IRT (SKI, 2000a) also commented that both corrosion mechanisms and kinetics must be studied further, especially bearing in mind the role that iron is considered to play in maintaining reducing conditions in a leaking canister.

In the authorities' view, SKB's selection of corrosion values for the iron insert (realistic value 0.1 µm/year, pessimistic value 1.0 µm/year) is based on too few data (even if both experiments and calculations are included). The importance of this uncertainty should be investigated, for example, by studying a larger corrosion rate interval. Another important objective should be to obtain a better basis for identifying the important rate-determining mechanisms for very long time-frames.

1.4.4 Buffer and Backfill

Certain important properties that are of particular importance for the performance of the bentonite and backfill are presented in this section. These properties must be further investigated in comparison with the information presented in SR 97.

Chemical Stability of the Bentonite
In the view of the authorities, the properties of the bentonite as a function of pH, temperature, pressure, particle size distribution and ionic strength should have been described in greater detail. KASAM has also made this point. To the extent that the function of the bentonite is affected by variations in any of these parameters, it is important that this should be presented more specifically.

Erosion of the Buffer and Backfill
SKB has identified mechanical and chemical influences as two causes of erosion of the buffer and also states that the risk of erosion is low in both cases. The conclusions are based on model calculations, laboratory experiments and field data from Stripa.

However, the authorities are not completely convinced that the processes are unimportant for the performance of the bentonite in the repository. Above all, any erosion that does occur should be considered as a source of colloid formation in the repository.

The authorities also point out that a high groundwater or rock matrix salinity would reduce the water uptake (or swelling) capability of the bentonite and backfill and, thereby, might be a cause for risk of piping. This should be studied further by SKB.

Water Saturation and Swelling of the Bentonite
According to SKB, full water saturation of the bentonite is reached within a few years, if the water supply from the rock is sufficient (unlimited). If the water supply from the rock matrix and fractures to the deposition holes is very low, SKB assumes that the buffer will be saturated by the water reaching the deposition hole via the backfill which, in itself, can lead to an uneven pressure load on the canister.

The authorities maintain that the single decisive factor for a rapid and homogeneous saturation of the bentonite in the deposition hole is an evenly distributed availability of water in the deposition hole walls, and this has not been demonstrated in SR 97. If this cannot be achieved, the swelling of the bentonite from uneven water saturation will probably result in an uneven load on the canister in the deposition hole. In turn, this can affect the mechanical integrity of the copper canister.

SKI's consultant, Sällfors (SKI, 2000c) points out that a high pore pressure in the surrounding rock (the hydrostatic pressure at a depth of 500 m is 5 MPa) will probably not occur during the operational phase. The pore pressure will probably not be restored to its original state until after repository closure. This could mean that the bentonite will not be saturated at the rate assumed by SKB. Consequently, in the authorities' opinion, greater attention should be paid to the disposal sequence and to how fast the pore pressure can be restored.

1.4.5 Geosphere with Site Investigations

Site Data

One of SKB's intentions in conducting SR 97 was to compare three different geographical sites in Sweden and show how final disposal could be safely achieved at these sites. The authorities find this work laudable. However, there is a strong variation in the data used for the three sites and SKB has not clearly demonstrated to the reader how it has used and evaluated the data in order to obtain a reasonably equal basis for the analysis.

This opinion is supported by SKI's consultant Tirén (SKI, 2000c) who states that the geological and structural geological presentation of the three sites vary considerably as do the degree of detail and volumes studied. A more transparent and systematic compilation of the data used in the analysis is necessary.

In Voss's view, (SKI, 2000c), it is doubtful whether the SR 97 evaluation of Ceberg is meaningful, bearing in mind that 20 year-old data have been used, which indicate that the transmissivity is the same for the fractures as well as the rock. This obvious error is probably due to the limited database used.

Through work commissioned from the consultants, Saksa and Nummela (1998), SKB has described alternative geological structural models and the uncertainties associated with these models. However, the results have not been taken into account in the scenario analysis.

The overall evaluation of the authorities is that, in spite of the different objectives of the investigations carried out at the sites and the considerable spread over time, SKB has nevertheless managed to use the data in an acceptable manner.

Geosphere Modelling

On one hand, SKB's aim is to describe in detail the sites in its reports but on the other hand, SKB only uses a small part of this information in its analysis. In the authorities' opinion, SKB has not made optimum use of all of the information to determine uncertainties in the model calculations.

In Geier's opinion (SKI, 2000c), since SKB has used a stochastic-continuum model with a low resolution (a smallest block scale of 25 m), minor water-bearing fracture zones (less than about 100 m in length) cannot be taken into account in the model. This must be viewed as a distinct limitation even if SKB means that fracture zones on the order of magnitude of 10-1,000 m have partially been taken into account in the case of Aberg (although not in the case of Beberg and Ceberg).

Link between the Safety Assessment and Site Investigation
Tirén (SKI, 2000c) states that in SR 97, SKB has not given the reader any concrete evidence of the contribution of the study to a specification of the factors upon which the selection of sites for site investigation will be based. Furthermore, SKB has not derived the requirements that should be made on a site investigation, which the authorities have also noted.

The IRT (SKI, 2000a) also states that SKB has not fulfilled the objective that SR 97 should provide a base for the specification of site selection factors and preliminary function requirements with respect to engineered barriers. However, the IRT also states that SKB is working on this issue separately.

One consequence of SKB's assumption concerning more or less intact engineered barriers throughout the repository lifetime is that the geosphere assumes a subordinate role as a barrier in SR 97. In Voss's opinion (SKI, 2000c), SKB has not exploited the possibility of, on the basis of geoscientific, primarily hydrogeological differences, improving the repository design and investigating the safety-related importance of the difference between sites.

SKB considers the description of the initial state of the geosphere to be a compressed form of a site description adapted to the needs of the safety assessment. In the opinion of the authorities, SKB should, in its planned site investigation programme, clarify the link between important safety assessment parameters as reported in, for example SR 97, and how these could be measured in the site investigations. In this context, the authorities emphasize the importance of not fixing the variables on the basis of existing safety assessment models. Otherwise, there is a risk of overlooking information of importance for the safety assessment. Feedback between the development work on the safety assessment and the site investigation is absolutely necessary, for this and other reasons.

In summary, the authorities consider that the link between the needs of the safety assessment and the site investigations is maintained by SKB's programme, on the whole, but that this issue has not been investigated to the desired extent in SR 97. SKB has stated that work on this issue is being conducted outside SR 97 and that the work will be presented in future RD&D programmes.

1.5 Conclusions of the Authorities

System Description Methodology
SKB's new method for system description using THMC diagrams is a valuable contribution to safety assessment methodology. In SR 97, SKB has not yet been able to

make full use of the method. In the authorities' opinion the method can, and should be further developed. However other methods must also be used to examine the evolution of the barrier system and functions from different aspects. The documentation of expert judgements made in connection with system description and in the formulation of scenarios must be improved in future safety assessments. In the authorities' view, in SR 97, SKB has avoided analyzing the impact of certain potentially unfavourable processes in detail. In future safety assessments, the consequence analysis may have to be expanded to include additional processes in order to improve the description of the risk situation.

Fuel

In the authorities' opinion, SKB's description of the fuel properties is acceptable but the uncertainties in the fuel composition must be studied in greater detail. In future safety assessments, the authorities expect a more complete description of the impact of burnup variations. The specific properties associated with MOX fuel may also have to be described in greater detail, as well as the occurrence of certain activation products such as C1-36 and C-14 in the metal components of the fuel.

Canister

Heat transport in the barrier system is a relatively well known process. However, bearing in mind the possibility of thermal degradation of the buffer at an early stage, SKB should improve its description of heat transport from the canister surface to the buffer. In the authorities' opinion, SKB must also show that the design requirement of a maximum of 0.1 % defective canisters is technically feasible. Progress has been made in model studies of the mechanical stresses on the canister due to the swelling of the surrounding buffer. However, the authorities recommend that these studies should be supplemented so that the entire time sequence is covered.

The corrosion resistance of the canister is one of the most important issues in a safety assessment of the KBS-3 method. The corrosion issues that must be described in greater detail in future safety assessments include stress corrosion, microbial effects and corrosion of the iron insert. The authorities recommend that SKB should immediately summarize the current state of knowledge on copper corrosion.

Buffer and Backfill

In the authorities' view, the chemical stability of the buffer and backfill is relatively well known. However, the residual effects of heating at the earliest stage and the effect of the long-term chemical changes in the groundwater must be described in greater detail. Bentonite erosion should be considered as a potential source of colloids. Furthermore, in the authorities' opinion, SKB must continue to focus on the water saturation of the buffer. Methods are needed to show that the water saturation is rapidly and evenly distributed. If this cannot be done, the negative effects of uneven swelling etc. must be described in the safety assessment.

Geosphere with Site Investigations

There is a variation in the scope and quality of the available data for the three sites that have been studied. Nevertheless, the overall evaluation of the authorities is that SKB has managed to use these data in an acceptable manner in SR 97.

However, in future safety assessments, SKB should evaluate and describe the uncertainties in the geological models in a more exhaustive manner, for example, by developing alternative structural geological models as a basis for formulating calculation variations in the safety assessment. Prior to future site investigations, SKB should also compile a description of measurable data relating to hydrology, groundwater chemistry and structural geology. Other areas that SKB should work on include the description of small-scale fractures, feedback from preliminary evaluation to the modification of measurement programmes and the development of criteria for repository siting.

In the authorities' opinion, by placing too much emphasis on the stability of the engineered barriers, SKB has not been able to analyze the performance of the rock as a barrier to the desired extent. The authorities also find that SR 97 does not contribute to establishing a tangible link between the safety assessment's need for data and the requirements on site investigations. However, at the same time, the authorities are aware that these issues are being taken into account in work carried out in other parts of SKB's programmes and in international research. Therefore, in the authorities' opinion, an evaluation of these issues must be deferred until the review of SKB's RD&D Programme 98 Supplement.

2 Processes and Initial State in the Biosphere

2.1 SKB's Report

An overall description of the biosphere and assumptions for biosphere calculations is presented in the Main Report (Section 6.6, 9.10-9.11) and in a background report (Nordlinder et al., 1999). A more complete description of the biosphere for the three (hypothetical) sites is provided in Lindborg and Schüldt (1998). An overview of a limited set of processes is provided (Section 9.10.1).

2.2 Comments by the Reviewing Bodies

The handling of processes and initial states in the biosphere is not commented upon to any great degree by the reviewing bodies.

2.3 SKI and SSI's Review and Evaluation

It is positive that SKB, to a greater extent that before, is attempting to describe the processes that determine the transport (migration, turnover, accumulation) of radioactive substances in the biosphere. Nevertheless, the description is limited.

2.3.1 Description of Processes

The processes in the biosphere are described in very general terms, and the description is not presented in the same systematic manner as the processes for other parts of the repository system. To obtain an overview of the processes that have been taken into account, it is necessary to obtain information from several different reports.

SKB states that it is difficult to prepare a process description for the biosphere that is as strict and exhaustive as that for other parts of the repository. This statement should have been justified in greater detail. On the basis of previous work on biosphere structure, for example in international contexts, interaction matrices could have been used to describe the biosphere or specific ecosystems.

2.3.2 Transition from the Geosphere to the Biosphere

The issue of how the transport of radioactive substances from the geosphere to the biosphere is to be handled has been discussed for a long time, in Sweden and internationally. Various approaches have been taken, but no single method has yet gained general acceptance. This is partly due to the difficulty of making observations or of conducting experiments.

This is also reflected in SKB's handling of the transition between the geosphere and biosphere in SR 97. The processes and interactions that could occur are not described. For example, the interaction between the groundwater and surface water is not described in the report although this is of fundamental importance for the understanding of radionuclide migration to the biosphere. Instead, the radionuclides are assumed to be transported directly from the geosphere into the typical ecosystem studied. SKB maintains that this is a conservative assumption. However, in the authorities' opinion, this assumption must be better justified. Furthermore, no discussion of how this approach could affect the uncertainty of the final results is presented.

2.3.3 Changes in the Biosphere

The biosphere will change during the time-scales that are discussed for the repository. The description presented in SR 97 is essentially based on the present-day biosphere.

The safety assessment must describe one case with the present-day biosphere although this may not prevent changes in the biosphere from being dealt with, especially if such changes can be considered to be probable. In the authorities' view, the essential factor is that the identification and characterization of the typical ecosystem should be based on present-day conditions. Currently unknown or improbably ecosystems do not have to be taken into account. For example, it is not reasonable to include tropical rain forests, desert and ecosystems that are typical of such environments.

APPENDIX 2

1 Base Scenario

The authorities' comments on Chapter 8 (Base Scenario) of SR 97, Main Report are presented in this chapter.

1.1 SKB's Report

In the base scenario, SKB describes the expected evolution for the case where the repository is built according to specifications and the conditions in the environment are expected to be unchanged, in principle, and to correspond to present-day conditions. All of the canisters are assumed to be without any manufacturing defects and present-day climate conditions prevail.

In the base scenario, the overall purpose is to study the isolating function of the canister. If the integrity of the canisters is unbreached, this criterion alone is sufficient to demonstrate safety. Several auxiliary criteria, for example that the groundwater should be oxygen-free and that the buffer should have a low hydraulic conductivity can be "derived" from the integrity criterion and the intended function of the barrier system. The task of the base scenario is to demonstrate whether or not the integrity criterion and auxiliary criteria are met.

Changes in the environment that can be characterized as "known trends", such as the ongoing land uplift and the tectonic evolution, are included in the scenario. Changes in the biosphere, such as the infilling of lakes and the forestation of open landscapes are also included as well as repository resaturation.

SKB describes the evolution of the fuel, canister, buffer/backfill and geosphere in the base scenario, and classifies the processes as radiation-related, thermal, hydraulic, mechanical and chemical, on the basis of the THMC diagrams provided in the background report "Processes in the Repository Evolution". Based on these analyses, SKB states that the canister retains its isolating capability and consequently, radionuclide transport does not have to be treated in the base scenario.

1.2 Comments by the Reviewing Bodies

In the opinion of the National Council for Nuclear Waste (KASAM), on the basis of present-day knowledge of corrosion in pure copper in the environment in question, there is nothing to indicate that canister penetration would be expected. However this must still be verified for the weld joints.

In KASAM's view, the description of the base scenario in time-frames of <100 years, 100-10,000 years and >10,000 years is a pedagogical approach. This approach could have been used to a greater extent with the bentonite buffer and backfill in order to describe how their properties change with time in the new environment.

As far as canister corrosion is concerned, Uppsala University's view is that particular attention should be paid to bacterial corrosion.

1.3 SKI and SSI's Review and Evaluation

1.3.1 General Opinions on the Base Scenario

In the authorities' view, the analysis of Aberg, Beberg and Ceberg's chemical evolution in the absence of climate changes is less relevant. The chemical composition of the analyzed groundwaters reflects previous climate changes and it can, therefore, seem to be illogical to exclude future changes. Climate changes will most probably occur and the most natural approach would therefore be to integrate them into a base scenario. However, SKB's base scenario without climate changes could be useful as a reference case or special case (for example, to illustrate effects of human influence on the climate that cause future ice ages to be delayed).

Furthermore, in the authorities' view, considering the importance that the buffer has for the intended performance of the canister and for enabling for radionuclide isolation to assume a major role, a more extensive discussion and evaluation in SR 97 of possible malfunctions of the bentonite buffer would have been justified. The importance of the diffusive barrier of the buffer to radionuclide transport is illustrated in the climate scenario. It would also have been of interest if the base scenario had included a more complete analysis of defects which could have, for example, demonstrated the importance of the buffer in limiting copper corrosion. This type of analysis should also include alternatives where defective manufacturing, handling and application of the bentonite are studied.

Also the International Review Team (IRT) (SKI, 2000a) states that defects in the engineered barriers must be further investigated. This applies to the possible occurrence and type of significant defects in the canister as well as to possible defects in the bentonite or deposition-related defects. The authorities' opinion on the analysis of defects in the canister relates to the impact of the material's properties on copper corrosion (see Section 1.3.6 of this appendix) as well as the size of the defects analyzed (see Section 2.3.2 of this appendix).

In the base scenario, SKB does not comment any further on the conversion of the fuel in an intact canister other than to say that the radiation field could cause the formation of nitric acid through radiolysis of the remaining air and water and the formation of helium gas from alpha decay. However, these processes are not considered to have any importance for safety.

The authorities share KASAM's view (SKI, 2000b) that the description of the base scenario in time-frames of the initial 100 years, 100-10,000 years and after 10,000 years provides pedagogical clarity. However, at the same time, the authorities would like to call to mind SSI's regulations which stipulate that the protective capability of the repository for the first 1,000 years after closure should be specifically described. The relevance of periods after 10,000 years has been commented upon by the authorities (see Section 4.3.5).

1.3.2 Radiation-related Evolution

SKB considers that there is a good understanding of the radiation-related processes in the base scenario, which involves an intact canister. The availability of data and models of good quality is also considered to be good.

The authorities agree with SKB's conclusions. In the authorities' opinion, the physical processes concerned here (radioactive decay and absorption of radiation) are among the best known of the processes that must be taken into account in the safety assessment.

However, knowledge of the fuel inventory of certain activation products and transuranic elements is not as thorough, and this observation is made in Appendix 1, Section 1.4.2. However, this has little or no impact on the conditions that apply to the base scenario.

SKB discusses the concept of toxicity under this heading and illustrates this with curves showing how fuel toxicity decreases with time. Although, in the authorities' opinion, such decay curves are illustrative, there are limitations to the conclusions that can be drawn from them. With reference to these curves, SKB reaches the conclusion that the toxicity of the fuel is reduced to the level of the corresponding quantity of natural uranium after about 100,000 years. However, it should be observed that the solubility of certain radionuclides, especially I-129, in the fuel is so high that this comparison can only apply to cases where radionuclide migration does not occur (which in fact is correct for SKB's base scenario). This condition has also been pointed out by KASAM (SKI, 2000b).

1.3.3 Thermal Evolution

SKB states that the design criterion of a maximum canister surface temperature of 100ºC can always be achieved, either with a smaller quantity of fuel in the canisters or by maintaining a larger distance between them. SKB refers to Ageskog and Jansson (1999) for canister surface temperature calculations.

In the authorities' opinion, the calculations performed by Ageskog and Jansson (1999) show that the design criterion can be met by regulating the quantity of fuel or the distance between the canisters. SKI's consultants, Goblet and de Marsily (SKI, 2000c) point out that although SKB does not analyze the sensitivity for the assumptions concerning temperature evolution in the fuel (burnup, storage time etc.), the calculations show, in an adequate, but indirect manner, that this type of parameter can be optimized from the temperature requirement.

In SKB's view, the design criterion has been established to avoid boiling and the subsequent salinity increase on the canister surface, which would result in corrosion effects that are difficult to analyze. The authorities agree that such corrosion effects could be difficult to analyze, but consider that the justification for the design requirements must be improved, for example, by describing what is actually known about possible chemical changes and corrosion under the conditions that could occur if the temperature exceeds the design requirement.

In the calculations for heat transport in the rock, SKB uses a model with simplified assumptions on the near field geometry. In the authorities' view, SKB should describe the impact of this simplification when the results are presented. Goblet and de Marsily state that the maximum temperature in the region closest to the canisters is underestimated since the heat source is more widespread in the large-scale model (than in the model used to calculate the canister spacing and heat load).

SKB considers that the results from the thermal evolution calculations have no direct bearing on safety but are primarily used in the description of the mechanical and chemical evolution. In the authorities' view, the couplings between the thermal, mechanical, chemical and hydrological processes, particularly in the buffer, must be studied further, particularly in order to describe the saturation process. In Goblet and de Marsily's opinion, SKB has studied the couplings but has not updated them with the latest temperature calculations. They also consider that the chemical aspects, in particular, require further study (see also Section 1.3.4, Buffer/Backfill, in this appendix).

1.3.4 Hydraulic Evolution

Geosphere

Various aspects of the hydrogeological conditions and their evolution are described in several of the background reports to SR 97 and in different chapters of the Main Report. The fact that this information is presented in various places, which is partly a result of the choice of scenarios in SR 97, means that it is difficult to obtain a good overview of the hydrogeological evaluation and that much of the text is repeated in the background reports as well as in several chapters in the Main Report.

This section contains comments on the description of the hydraulic evolution in the base scenario, which only comprises the large-scale (regional) evaluation for the three sites. The detailed modelling in the local scale is described by SKB in the canister defect scenario and is therefore commented upon by the authorities in Section 2.3.7 of this appendix.

The authorities share the IRT's view (SKI, 2000a) that the reasons for the lower level of ambition with respect to the hydraulic description in the base scenario compared to the canister defect scenario are unclear. In the authorities' opinion, the hydraulic evolution for the base scenario needs to be studied in at least as much detail, since the hydraulic conditions affect the chemical evolution of the groundwater which in turn affects the crucial analysis of the isolating functions of the engineered barriers.

The analyses of the hydraulic evolution in the base scenario are limited to the effects of the ongoing land uplift and have only been performed in full for Beberg. The effects of land uplift is modelled for the first 5,000 years after closure. After this time, SKB considers that other climate conditions will dominate. In spite of this, the hydrogeological calculation results are used as input data for the model calculations of copper corrosion and the buffer evolution during time periods of 100,000 years. This lack of consistency reinforces the authorities' impression that the base scenario should be considered as a starting point for the calculations rather than an actual scenario.

Several of SKI's consultants (SKI, 2000c) would like to see a more systematic evaluation of model uncertainties in the regional flow models. Glynn questions the simplified representation of the rock in the form of fracture zones and rock mass to describe the continuous distribution of different major water-bearing fractures. Glynn also considers that the selected domain sizes for the regional models are far too small. Voss would like to see a systematic discussion of uncertainties and an evaluation of the interpreted fracture zones in the hydrogeological models with respect to the deficient data outside the investigated sites. Geier questions SKB's motives in the background report "Waste, Repository Design and Sites" for only specifying uncertainty intervals in hydraulic conductivity for the regional fracture zones at Ceberg.

The IRT (SKI, 2000a) considers that SKB should, to a greater degree, integrate analyses of the hydraulic and geochemical evolution. Knowledge of the formation and chemical evolution of different types of groundwater could be used, for example, to test alternative hydraulic evolution models. Certain analyses of the historical evolution of the sites have been performed in SR 97, even if the analyses are not consistent for all three sites. The authorities' opinion is that an overall evaluation integrating various types of data is necessary to develop the geoscientific understanding of a site and its historical and possible evolution. The authorities assume that SKB, in its further work on site investigations, is planning to conduct such integrated analyses, both with respect to the need for measurement data and modelling.

In summary, the authorities consider that the regional modelling of hydrogeological conditions in SR 97 is extensive and generally of good quality even if certain aspects of the analysis methodology must be reinforced prior to forthcoming site investigations. The analysis of processes and properties that can affect the hydraulic evolution of the site is systematic, but the strategy for evaluating different hydraulic processes must be clarified, for example with respect to the selection of models and the handling of model and parameter uncertainties.

Buffer/Backfill

According to SKB, the base scenario must include a description of the condition the buffer has reached at saturation as well as an estimate of the length (in time) of the saturation process. The extent of the detail necessary in the description of the saturation process is stated in contradictory terms, such as "not important in the safety assessment" and what is needed is "a more detailed description of the hydromechanical evolution when the buffer/backfill is saturated with water". SKB's argument is that the long-term evolution of the system will be the same, regardless of the details of the saturation process as long as the end-state after saturation is known.

Furthermore, SKB states that the water saturation process in the buffer/backfill is dependent on the supply of groundwater to individual deposition holes or tunnels. SKB also states that the thermal properties of the buffer are dependent on its water content, which changes during the buffer saturation process. Moreover, the thermal evolution does not include any processes that directly affect the isolating capability of the repository.

In the authorities' opinion, "Processes in the Repository Evolution" contains a good description of the processes affecting resaturation and water transport. However, the authorities question SKB's statement that present-day understanding of the bentonite buffer water saturation process is adequate for the needs of the safety assessment. SKB itself states that the theoretical knowledge base for water saturation is not complete. Furthermore, there is no unambiguous experimental evidence to support SKB's assumption concerning the saturation process in the bentonite buffer.

In the authorities' view, the connection between the hydrothermal evolution and the mechanical and chemical evolution must also be better described with respect to the early evolution in the buffer, since also the long-term properties of the buffer can be affected by the environment and processes to which it has been exposed at an early stage (see also Section 1.3.3 in this appendix).

The fact that there is still a considerable need to improve the understanding of bentonite clay resaturation – even for the final disposal concepts in other countries – is emphasized by the extensive research conducted within several major international projects. SKB is itself conducting an extensive R&D-program at the Äspö Hard Rock Laboratory, and these experiments are expected to provide new insight into the area over the next decades.

1.3.5 Mechanical Evolution

In the base scenario in SR 97, SKB discusses the mechanical evolution of the canister, given the expected evolution of the buffer/backfill. The mechanical evolution of the buffer/backfill has been integrated into the description of the hydraulic evolution and is therefore reviewed by the authorities in Section 1.3.4 of this appendix. The effects of rock movements on the canister are also analyzed. A description is also provided of the mechanical evolution of the geosphere and its long-term stability.

In the authorities' view, the load cases identified by SKB cover the range of possible load cases that are of interest to analyze or describe. However, the authorities consider that SKB must describe in greater detail the assumptions used in the analysis for canister, bentonite and rock properties. SKB must also clearly state which aspects have been covered by the calculations and which have been neglected and why. This also applies to the simplifications made in order to perform the analyses.

SKI's consultant, Stephansson (SKI 2000c) also points out the difficulty that existing numerical codes have in adequately handling large displacements in the surrounding rock. The problem is complex, involving three different types of material that must be handled in the mechanical analysis. In the authorities' opinion, SKB must investigate the future need for model development and possible requirements on handling coupled effects. This applies, for example, to mechanical effects in order to show that the selected canister design can withstand SKB's current criteria with a postulated displacement of 0.1 m along a fracture intersecting a canister hole. The authorities note that SKB intends to re-do the calculations with different load cases for the current canister design. The 0.1 m criterion may then have to be modified.

SKB itself points out that calculations of canister strength can be improved with more realistic inhomogeneous material properties for different situations. SKB also mentions the possibility of improving the analysis of the hydromechanical evolution of the gap between the canister and buffer at an early stage. The authorities view this as two good examples of the need for future work.

SKB briefly discusses the period following the heat pulse and its possible impact on the rock mass properties. The authorities share Stephansson's view that there is a future need to study in more detail the effects of this cooling on the rock mass, especially the impact on the THM properties of the fractures as the stress situation changes.

1.3.6 Chemical Evolution

Groundwater Composition

The composition of the groundwater and its distribution in the bedrock at a candidate site should be analyzed and be included as an important part of the safety assessment, since it can provide many important clues on the evolution of chemical processes, climate and hydrology. Furthermore, certain groundwater components are of decisive importance to the stability of the barriers, such as pH, redox conditions and salinity. In the base scenario, SKB provides a general description of the composition of the groundwater at Aberg, Beberg and Ceberg and of its possible evolution under the influence of the land uplift but without any climate changes. The resaturation phase which starts in connection with the closure of the repository is also briefly described.

In the authorities' opinion, the analysis of the chemical evolution of Aberg, Beberg and Ceberg without climate changes but under the influence of land uplift is less relevant. These conditions must be considered to be unreasonable for all time periods exceeding 1,000 years. The chemical composition of the analyzed groundwater reflects previous climate changes and therefore the exclusion of future changes must be considered to be illogical (see also Section 1.3.1 of this appendix).

The authorities agree with SKB that the resaturation phase with a return to reducing chemical conditions will probably occur faster than previously expected, especially with the influence of microbial processes.

The quantity of organic material that may be left behind after closure or whether or not it is acceptable to leave large quantities of cement near to the deposition holes are not described in SR 97. In the authorities' opinion, any negative effects that can occur due to the presence of such material should be described.

The IRT (SKI, 2000a) raises issues that would improve the robustness and provide more transparent support to the safety assessment, if they were described in a better manner. These issues include an improved understanding of the origin and development of the groundwater and a better documentation and argumentation surrounding the conditions that would jeopardize the reducing conditions at repository depth.

Buffer/Backfill

The buffer surrounding the canister plays a key role in maintaining stable and favourable conditions near to the canister surface. Normally, the bentonite should ensure the following: slowing down and limiting the supply of corrodants (such as dissolved sulphide) by diffusive transport, limiting the microbial processes near the canister (such as sulphate reduction) and slowing down the transport of radionuclides from a defective canister. In a long-term perspective, it cannot be simply assumed that these and other important functions will be maintained, for example, that an excessive reduction in the swelling pressure and degradation of plasticity may not occur. In a short-term perspective, it must be ensured that full resaturation will occur so that the high temperature near to the canister surface does not degrade the bentonite properties.

The backfill comprises a mixture of crushed rock and bentonite. The function of the backfill is to seal the access and deposition tunnels so that rapid transport paths are not formed in the rock. Since the swelling pressure in the backfill is lower than that in the buffer surrounding the canisters, the impact of groundwater with a high salinity could be of greater importance.

In the base scenario, SKB describes how bentonite can be affected by chemical processes. SKB states that illitization, cementing reactions and buffer erosion/colloid formation will probably not occur to any significant extent over time-scales of 100,000 years. On the other hand, SKB's view is that ion-exchange reactions (from Na-bentonite to Ca-bentonite) as well as the dissolution of accessory minerals (calcite and pyrite) will probably be considerable, although this will only have a marginal impact on the bentonite functions. SKB does not describe in greater detail the chemical evolution of the backfill, but states that this issue must be treated in future safety assessments.

The authorities have no objection to the description of the long-term changes in the bento-nite in the base scenario. However, in the authorities' view, the level of knowledge of bentonite mineral reactions should be further developed. The most significant uncertainty is probably linked to the long-term evolution of the groundwater chemistry, which is commented upon in connection with the climate scenario. Since the cases that could affect the buffer to the greatest extent are included in the climate scenario, the authorities consider that it is unsuitable to analyze the isolating function of the repository in the base scenario.

Copper Canister Corrosion
Bearing in mind that the purpose of the base scenario is to study the isolating function of the canister, the authorities consider that the description of copper canister corrosion is too brief. In its review of SKB's RD&D Programme 98, SKI stated that the central factor within the corrosion area is how knowledge of the different corrosion processes is used in the assumptions and analyses upon which the thickness of the copper is based and that SKB should therefore update and compile the knowledge of different copper corrosion processes in a repository environment. This updated compilation of knowledge and a detailed description of the application of models and data should be used in future safety assessments.

The IRT (SKI, 2000a) states that SKB has developed a sound and convincing scientific basis for the description of the evolution of the copper shell over a long time. However, additional experimental studies of certain corrosion processes are needed, including corrosion in the presence of oxygen (e.g. before reducing conditions occur after deposition) and conditions for localized corrosion.

In the opinion of the authorities, the analysis lacks a description of how the nature of the copper material affects corrosion, especially any differences between the weld joints and the rest of the material. This includes grain size, initial defects that are smaller than the acceptance criteria and, particularly, surface defects (due to deviations from the specified surface finishing, handling defects etc.).

As previously stated, the authorities share the view of the IRT (SKI, 2000a) that the analysis of copper corrosion should also include the impact from the hydraulic, and particularly, the geochemical evolution of the groundwater as a result of climate changes.

Stress corrosion is not dealt with at all and SKB refers to the background report, "Processes in the Repository Evolution". As was previously mentioned, the authorities consider that SKB must show, more clearly, that stress corrosion of the copper shell cannot occur (see Appendix 1, Section 1.4.3).

Microbial processes at the canister surface that can affect copper corrosion is another important issue where additional data is necessary to support SKB's view that bacterial sulphide corrosion can be excluded as a process in the repository environment.

The authorities agree that very high chloride ion concentrations are required for chloride to be important for copper corrosion. On the other hand, in the authorities' opinion, corrosion would be possible at pH values higher than 3 at temperatures exceeding 100ºC (Hermansson and Eriksson, 1999). Situations with a high temperature and high chloride ion concentrations could be possible at an early stage after deposition. Therefore, in the authorities' opinion, a more comprehensive and balanced description is necessary.

Appendix 2

2 Canister Defect Scenario

2.1 SKB's Report

The canister defect scenario postulated by SKB is based on initial defects caused by manufacturing procedures. In the absence of data from series manufacturing of canisters, SKB assumes that a maximum of 0.1% of the canisters are associated with such initial defects. Canister defects caused by corrosion or mechanical effects are excluded and this is discussed in connection with the base scenario and the tectonics/earthquake scenario. In the canister defect scenario, it is assumed that climate and biosphere conditions do not change with time.

After a certain delay, the initial defects result in leakage and radionuclide migration, which is analyzed and discussed in the chapter. The radionuclides that are expected to reach the biosphere before they have decayed result in a hypothetical dose and risk contribution. The comparisons with SSI's radiation protection criteria presented by SKB are based on the calculated dose and risk for this scenario.

This scenario is, to a greater extent that the others, based on quantitative analyses, focused on basic mechanisms for retention and radionuclide migration. In SKB's analysis, retention mechanisms in the engineered barriers are accorded considerable importance, such as delayed transport from a defective canister to the surrounding buffer, slow fuel dissolution, limited solubility of certain radionuclides and adsorption of radionuclides on the buffer mineral. Site-specific properties only enter into the calculations via analyses of hydraulic properties for Aberg, Beberg and Ceberg. The hydraulic analysis is the basis of the radionuclide calculations in the geosphere and of the identification of release points to the biosphere. Hypothetical doses to man are then calculated by converting the outflow to the biosphere into radiation dose using dose conversion factors developed for common biosphere types. SKB does not consider that it can predict the biosphere that will evolve in a certain region and, in most cases, uses the biosphere types that are considered to be most unfavourable (such as peat bogs) in its assumptions.

Calculation results are reported for cases with input data that are considered to be reasonable (namely neither optimistic or pessimistic) as well as for cases with combinations of reasonable and pessimistic data. Furthermore, a number of cases are reported where a vital safety function is completely eliminated in order to show the relative importance of the different barriers. Finally, SKB has prepared risk analyses for Aberg, Beberg and Ceberg for the most important biosphere types (wells and peat bogs). These risk analyses are based on statistic compilations of results from random realizations with pessimistic and realistic data.

2.2 Comments by the Reviewing Bodies

The National Council for Nuclear Waste (KASAM) states that future safety assessments should be based on realistic assumptions regarding canister defects based on tests conducted with a relatively large number of canisters.

On the subject of the bentonite, KASAM's opinion is that the chemical properties and their natural variations must be better investigated. In KASAM's view, the knowledge of bentonite properties is not utilized in an optimum manner since only conditional parameters are utilized to describe sorption. More sophisticated sorption models should be developed for the most important radionuclides. It is also important to describe the changes in the bentonite buffer and backfill that can be expected due to climate-driven geochemical and hydrological changes.

KASAM considers SKB's work on developing models to describe transport and concentration processes in the biosphere to be valuable. However, in KASAM's opinion, the account presented in SR 97 is not sufficiently transparent. A reader has difficulty in following the entire calculation chain which finally leads to the dose contribution to man. KASAM would like to see detailed calculation examples in future safety assessments. Furthermore, the calculation models used should be further developed since they can still be considered to be primitive. The ultimate goal of the EDF factors should be to obtain time-dependent dose conversion factors which are justified by the major differences in the half-lives of the different radionuclides.

In the view of Pereira, Stockholm University, SKB should have used a more systematic probabilistic approach in the radionuclide transport modelling. In Pereira's view, SKB's risk analysis is brief and has actually only been prepared as a supplement to what is basically a deterministic analysis. This deterministic approach is too limiting since it only provides individual samples which make it difficult to obtain a good overview with a reasonable number of calculations.

According to Pereira, the background report "Data and Data Uncertainties" is not complete with respect to the discussion of the probabilistic distributions. Probability distributions should have been discussed for sorption data, for example, and not only hydrological parameters. If there is a lack of knowledge about one parameter, this is a good reason to illustrate the importance of that parameter by using a distribution that covers the uncertainty in the data.

Furthermore, Pereira considers that conceptual uncertainties with respect to radionuclide transport are not explicitly described (such as COMP23, FARF31), in the same way as has been done for the hydrology models. The reduction of complex 2D and 3D models to 1D models could introduce conceptual errors that are difficult to interpret. Sensitivity analyses performed with the highly simplified models for consequence analysis can be questioned taking this into account. Instead, these should be performed using the more detailed research models.

Kurt-Olof Carlsson questions the completeness of the canister defect scenario, in the light of new results from the USA concerning plutonium transport.

Uppsala University would like to see a description of the importance of gas transport from great depths for repository safety.

In Tord Jonsson's opinion, the choice of reference fuel should be justified by a comparison with the burnup for the fuel already stored in CLAB. Furthermore, the irradiation history should be taken into account in order to obtain more reliable information on fission product distribution. Jonsson mentions a phenomenon called "bonding" where the fuel becomes attached to the cladding. The gap between the fuel and cladding does not normally exist in high burnup fuel and the free volume is redistributed to cracks in the fragmented fuel.

2.3 SKI and SSI's Review and Evaluation

2.3.1 Radionuclide Transport and Retardation Processes

The quality of the safety assessment is completely dependent on the scientific understanding of the basic processes and the data upon which radionuclide transport and consequence analysis are based. In SR 97, these aspects are documented in two background reports, one dealing with process understanding ("Processes in the Repository Evolution") and the other justifying the choice of data for the calculations ("Data and Data Uncertainties"). In the authorities' opinion, SKB has basically chosen a good method of structuring the information required and the structure makes it possible to gradually develop and refine the material prior to future safety assessments. However, the authorities agree with Tsang, Wilmot and Crawford et al. (see Section 4.3.11) who state that the justification for the countless decisions involved in a safety assessment such as SR 97 must, in future, be documented in a better manner than in the two background reports specified above.

In connection with its definition of the conceptual models for radionuclide transport and consequence analysis, SKB eliminates many of the processes described in "Processes in the Repository Evolution". Furthermore, the conceptualizations used almost always mean that the processes taken into account are simplified to varying degrees which, in turn, affects the choice of parameters relating to the models. This is a natural process that is unavoidable in order to obtain a calculation model that is coherent. However, in the authorities' opinion, SKB should aim to more systematically describe and investigate the uncertainties and simplification errors that result from this approach and how they have been handled in the safety assessment.

More specific comments concerning the processes, models and data included in the consequence calculations are provided in the following sections. A more complete and detailed evaluation is available for certain sub-areas and this is provided in the report presenting the opinions of SKI's consultants (SKI, 2000c).

Radionuclide Solubilities
Arthur and Zhou (SKI, 2000c) raise the question of whether SKB's thermodynamic database for radionuclides (Nagra/SKB-97TDB) can be considered to be adequately reliable. Arthur and Zhou consider that it is doubtful whether the author of the database made sure that all of the data are compatible with respect to basic thermodynamic definitions. Bruno et al. (1997) have evaluated the accuracy by comparing calculated solubilities with radionuclide concentrations in natural systems and experiments with spent nuclear fuel. However, in Arthur and Zhou's opinion, since the basic requirement of internal consistency must be met first, there is reason for SKB to verify and update its database so that it can be shown that it meets these quality requirements.

Arthur and Zhou consider, in general, that the chemical evolution in the near field has been accorded relatively little attention in SR 97, compared with safety assessments from other nuclear waste programmes (McKinley and Savage, 1994). The most relevant results are presented in Bruno et al. (1999). However, these results are not used as a basis for the solubility calculations. Arthur and Zhou recommend that SKB should refine its methods of estimating the pore water composition in the bentonite, by taking into account the fact that ion-exchange reactions also involve tetrahedral and octahedral positions. It is also preferable that parameters in ion-exchange and surface complexation models should not be exclusively based on results from short-term experiments (see for example, Savage et al., 1999).

Ekberg (SKI, 2000c) considers that SKB should pay more attention to how uncertainties are handled in the estimate of radionuclide solubilities (Bruno et al., 1997). A more detailed examination of how different basic factors (stability constants, water chemistry etc.) affect the calculated solubilities is needed. Available methods can be used in order to more systematically propagate quantitative measures of different types of uncertainties further in the calculation chain (Haworth et al., 1998; Helton 1993 and 1994). These have been used in the nuclear waste programme conducted in other countries and can also be used in SKB's safety assessments.

Even if the solubilities calculated in SR 97 are probably conservative, the authorities and several of SKI's consultants consider that the solubility calculation method can be improved. Certain premises for solubility calculations can be clearer in future analyses, such as data handling, the propagation of uncertainties and estimates of pore water composition in the bentonite buffer. Furthermore, the authorities recommend that SKB evaluate the types of pore water composition that can be expected inside a damaged canister, since SKB anticipates a very limited transfer between a defective canister and the surrounding buffer. Processes affecting pore water composition inside a damaged canister include fuel dissolution, radiolysis or corrosion of the iron insert.

Bentonite Buffer and Backfill
Stenhouse (SKI, 2000c) points out the importance of taking into account current and expected pore water composition in determining and using the Kd values for bentonite (for example Cho et al., 1995). Such considerations are either missing from the underlying references to SR 97 (such as Yu and Nertnieks, 1997) or contradictory or unclear views are presented. For example in Ochs (1997), bentonite components are considered to determine the pore water composition primarily while Bruno et al. (1997) also

assumes that the opposite can apply, namely that the groundwater composition is the determining factor. Bruno et al. (1999) later obtained completely different pore water compositions for bentonite but these are not used in SR 97. This is also pointed out by SKI's consultants, Arthur and Zhou (see above).

According to Stenhouse, the Kd values determined using batch experiments may be associated with major errors. Consequently, the results from such experiments must be compared with results from diffusion experiments for all important radionuclides. Diffusion experiments can be considered to be more representative of the expected conditions in the repository. Thus, SKB should make sure that the experimental data are adequate. On the basis of comparisons with other programmes, Stenhouse is of the opinion that SKB's realistic Kd values are reasonable. However, SKB's choice of pessimistic values is considered to be dubious since Kd values that are two orders of magnitude lower than the realistic values will probably be required to cover the entire uncertainty interval.

The authorities propose that SKB should evaluate several different models in parallel to estimate the long and short-term evolution of the pore water composition in the bentonite in order to study conceptual uncertainties. The results will also provide a measure of the uncertainties and these should be consistently utilized in the modelling of sorption and solubilities in the buffer. It should be shown that the sorption data used are either compatible with the entire interval of expected pore water composition values or that several sets of data are available that cover the entire interval. Furthermore, the authorities recommend that SKB take into account the depletion of the redox capacity of the buffer which is caused by radiolysis, which primarily applies to cases where plutonium and americium are retained in the buffer and possibly the canister.

Buffer/Backfill-Geosphere Interface

In SR 97, it is assumed that the buffer and backfill will retain their transport properties for periods up to one million years. However, it would be of interest in the description of transport between the buffer/backfill and surrounding rock to evaluate the processes that could lead to changes in the transport properties. For example, it is not unthinkable that the backfill could be converted so that a preferential transport pathway is formed near the roof of the deposition tunnels. Changes in filled boreholes may also have to be taken into account.

Geosphere

In the view of Stenhouse (SKI, 2000c), SKB's choice of realistic Kd values for transport in the geosphere are generally reasonable, although in his view, the uncertainty interval discussed is probably too limited. In the background report, "Data and Data Uncertainties", the intervals are described as broad. However, Stenhouse points out that they cannot even be considered broad compared with the variability that is measured in the experiments. Since the uncertainty of the water chemistry and mineralogy must be added to the experimental uncertainty, the authorities agree that there may be reason to question SKB's choice of pessimistic values. SKB is recommended to investigate the choice of conservative values in greater detail using sensitivity analyses. These could result in the conclusion that additional experiments are required since the experimental data for certain radionuclides are very limited. Stenhouse proposes that the uncertainty interval for certain radionuclides (such as americium) should be increased in order to take into account the effects of the occurrence of humic substances.

The flow-related transport parameters are summarized in SR 97 with the F factor which contains three parameters: flow-wetted surface available for sorption and matrix diffusion, transport stretch and groundwater flow (Darcy flow). The model calculations in SR 97 and other safety assessments show that the F factor is a crucial determining factor for the capability of the rock to limit transport and leakage of sorbing radionuclides to the biosphere.

The International Review Team (IRT) (SKI, 2000a), Wörman and Xu, Voss and Geier respectively (SKI, 2000c) consider that the evaluation of the flow-wetted surface contains considerable conceptual uncertainties and is inadequately supported by data. Voss points out, for example, that radionuclide transport can be unevenly distributed in the rock fractures which would reduce the available surface for sorption and matrix diffusion. SKB discusses these issues in the background report "Data and Data Uncertainties" but maintains arbitrarily that the method selected for estimating flow-wetted surface from conductive fracture frequency in boreholes is adequately pessimistic. However, in the authorities' opinion, the chosen values (reasonable value = 1 m^{-1} and pessimistic value = 0.1 m^{-1}) do not necessarily reflect the uncertainties that are associated with this important parameter. The authorities assume that SKB, in its further work on the site investigation programme will prioritise the development of measurement methods that can reinforce the data for the flow-wetted surface.

SKB does not explicitly treat the impact of colloids in SR 97, but refers to previous studies that have shown that colloids probably have a low impact on radionuclide transport (Allard et al., 1991). The authorities agree with SKB that colloid transport probably will not be of decisive importance as long as the buffer remains intact and as long as the groundwater composition does not change significantly. However, there may be cases where a large volume of undiluted groundwater would result in higher colloid concentrations and could affect the buffer.

The impact of colloids should also be evaluated for cases where the buffer does not perform as intended, for example, due to defects arising from manufacturing and emplacement. In waters near the surface and surface waters, colloids can provide the dominant transport path. Even if a rough calculation shows that colloid transport makes a small contribution to the dose and risk, this does not exclude the fact that radionuclides that normally have a very limited mobility, such as actinides, would reach the biosphere relatively rapidly. These radionuclides are at least potentially significant and can also have completely different properties than the relatively soluble radionuclides that normally result in a significant dose and risk contribution. Therefore, in the authorities' opinion, a quantitative illustration of the impact of colloidal radionuclide transport is warranted and this should be included in the consequence analysis.

2.3.2 Defect Analysis for the Canister

SKB states that the number of canisters with initial defects cannot be estimated today. In SR 97, the assumption used is 0.1 % defective canisters but the actual number is expected to be lower. However, this postulated design criterion is not applied in the realistic case in the analysis. Instead, it is assumed that only 1 canister has initial defects, which corresponds to a defect frequency of about 0.025 %.

The authorities agree with SKB in that a realistic estimate of the number of defective canisters can only be made when series manufacturing has started. Since there is no theoretical or empirical basis to start from, it is not possible to judge whether or not 0.1 % is a reasonable estimate. In the design basis requirements for the canister (Werme, 1998), the number of canisters with more undetected defects than permitted by the acceptance criterion may not exceed 0.1 %. However, the acceptance criterion is not specified. On the basis of a line of reasoning that is presented in “Data and Data Uncertainties”, SKB assumes a defect size of 1 mm^2 in the canister defect scenario. However, the authorities consider that SKB should report the impact of minor defects (which cannot be excluded in the authorities’ opinion) as well as defects of a different form (such as the peripheral crack that the line of reasoning is based on in “Data and Data Uncertainties”).

2.3.3 Defect Analysis for the Buffer

SKB does not describe any cases in SR 97 where the buffer does not perform as intended. In the authorities’ opinion, as in the case of the canister, SKB should describe the deviations and defects that can occur in connection with the acquisition of material, manufacturing of bentonite blocks, emplacement of bentonite blocks and resaturation. The possible impact of these defects should be studied within the framework of the safety assessment.

2.3.4 Criticality Analysis

SKB states that, with the current canister design, criticality cannot arise if water leaks into the canister, assuming that the fuel is intact and the fuel burnup is taken into consideration. Furthermore, SKB maintains that the probability of criticality outside the canister due to the leakage of fissile material is very low, and that the consequences of any criticality would be “small”.

The authorities agree that criticality is not likely, providing that there is adequate fuel burnup and that the fuel geometry remains unchanged. This conclusion is supported by a recently conducted SKI study (Hicks and Prescott, 2000). However, it is a weakness that the burnup must be taken into consideration since this entails considerable administration and probably also control measurements when the fuel is encapsulated.

In the authorities' opinion, SKB should further investigate the importance of the considerable occurrence of iron in the canister and the risk of criticality in connection with the deposition of low burnup fuel and possibly MOX fuel. Furthermore, in the authorities' opinion, an in-depth analysis of the probability of criticality in the long-term is necessary.

2.3.5 Defective Canister Evolution

In previous safety assessments of repositories based on the KBS-3 concept, such as SITE-94, it was assumed that the function of the copper canister as a physical barrier would cease with the intrusion of the surrounding groundwater into the canister via a defect. The reason behind this assumption is that the copper canister will be considerably deformed through swelling caused by the formation of corrosion products from the iron insert. In SR 97, SKB has used a new approach based on detailed model studies of the mechanisms that are expected to deform the canister. The conclusion drawn is that a major canister deformation does not occur until 200,000 – 500,000 years after the groundwater is originally supplied. In SKB's opinion, based on model studies conducted by Bond et al. (1997) and Takase et al. (1999), the highly prolonged process is dependent upon the fact that hydrogen gas, which is formed during iron corrosion, builds up a counterpressure (against the hydrostatic pressure) which strongly limits the supply of groundwater (which is necessary to maintain corrosion).

SKI's consultants, Arthur and Zhou (SKI, 2000c) consider that SKB's canister model is generally based on sound principles but that the impact of the chemical processes has been excessively simplified. They point out that the real system is partly open unlike the experimental system upon which SKB bases its conclusions. The supply of CO_2(g) and H_2S(g) may have to be taken into account, and this could lead to results showing that corrosion products other than magnetite are important. Furthermore, in the opinion of Arthur and Zhou, the mechanism for corrosion without a previous condensation stage is unclear. Arthur and Zhou further point out that SKB's consultants have not taken into consideration the hydrogen leakage to the surrounding buffer via dissolution in the pore water. Grambow (SKI, 2000c) questions whether the aerobic corrosion mechanisms that are caused by the formation of oxygen and other oxidants from the radiolysis of spent nuclear fuel have been adequately taken into account. These reactions are expected to be considerably faster and to result in other corrosion products. SKB's consultants, Takase et al., consider that slow corrosion mechanisms and corrosion rates as well as the effects caused by the extrusion of bentonite into the canister via the original defect are associated with significant uncertainties. The extrusion of bentonite into the canister can result in water being sucked into the canister via capillary forces. SKB's consultant, Bond et al., considers that the greatest uncertainty is associated with the use of corrosion rates that have been obtained in short-term experiments to extrapolate corrosion for 100,000 years.

In the opinion of the IRT (SKI, 2000a), the knowledge base on how the canister insert limits radionuclide transport is not as mature as that on copper corrosion. In the IRT's opinion, issues that must be studied further include the mechanical stability of the insert, the size and frequency of possible defects as well as corrosion mechanisms and corrosion kinetics for the iron insert.

It is hardly necessary to point out the significance of SKB's defective canister model, since the results indicate that radionuclide release is completely eliminated for time periods of up to 200,000 years. This adds an entirely new safety function to the KBS-3 concept. However, in the authorities' opinion, SKB has not yet shown that the proposed model actually predicts the probable evolution of a defective canister and does not merely comprise an idealized calculation case. The difficulty lies in the fact that SKB's model is based on the coupled effects of a number of processes that are very different from each other (corrosion, gas transport, groundwater flow, mechanical effects). Such a strongly coupled system may be sensitive to minor variations in initial states, boundary conditions, rate constants and the impact of secondary processes that have been neglected in SKB's analysis.

In the opinion of the authorities, certain assumptions concerning mechanical effects on the canister can be called into question. SKB's consultants, Bond et al., state that the copper shell is breached when the deformation exceeds the copper fracture strain, namely 29 %. However, since this process is very slow, creep should be the process determining the design. This would mean that the canister only withstands the creep fracture strain which is expected to be considerably lower than 29 %.

The authorities recommend that SKB should prepare a more detailed basis for future analyses including studies of rate-determining mechanisms, kinetic data, geochemical evolution inside a damaged canister, as well as transport processes inside and around a canister. It would also be valuable if SKB could conduct some form of experiment demonstrating the interaction of the most essential processes.

To summarize, the authorities are positive to the fact that new knowledge of the retardation mechanisms in the near field are identified and agree that a defective canister probably has important barrier mechanisms that must be further investigated. However, at the same time, the authorities state that the results from the canister model should not be included in the consequence analysis at this early stage. This would be imprudent in view of the significant conceptual uncertainties in the model and in view of the fact that the experimental data are limited.

2.3.6 Fuel Dissolution

SKB's analysis of fuel dissolution is based on a mathematical model of radiolysis (Eriksen, 1996) of water near to the fuel surfaces, reactions between radiolysis products in the water and the oxidation of uranium dioxide ($UO_2(s)$). A necessary assumption of the model is that a high hydrogen gas pressure can be maintained, which is considered to occur continuously due to the corrosion of the iron insert and radiolysis. The calculations show that an almost constant dissolution rate of 10^{-8} shares per year is reached at a hydrogen gas pressure exceeding 0.5 MPa. For the dissolution rate to be as low in the calculations that are reported, atomic hydrogen must be formed, which then consumes a large part of the oxidants which would otherwise be able to react with the spent fuel.

In certain previously performed calculations, the dissolution rate is conservatively assumed to be proportional to the α activity with the proportionality constant calibrated via experiments using spent fuel. SKB has not used this assumption in SR 97, since the goal has been to obtain a realistic dissolution rate rather than a conservative one.

Most of the radionuclides are considered to be in a solid solution with the UO_2 matrix and are therefore assumed to dissolve proportionally to the above discussed dissolution rate. A smaller portion of the radionuclides is in a more available form, either in the gap between the fuel and the cladding or in the grain boundaries between the crystals in the UO_2 matrix. SKB conservatively assumes that this small portion of radionuclides can be dissolved immediately as soon as the fuel comes into contact with the groundwater ("instant release fraction", IRF).

Grambow (SKI, 2000c) points out that SKB's model for fuel dissolution is associated with significant uncertainties and that these have to be more fully identified and analysed than in SR 97. The fuel model has not been documented and tested to such an extent that a detailed evaluation is possible. Grambow has developed a parallel model to attempt to reproduce SKB's results. It was possible to reproduce the results but several minor changes in the models resulted in dissolution rates that were considerably higher than 10^{-8}. These alternative variants could not be excluded in any obvious manner.

Uncertainties are primarily associated with the reaction order for the heterogeneous reactions, how radicals are handled in the model as well as the fact that rate constants have been developed in experiments using unirradiated $UO_2(s)$ instead of spent fuel. SKB does not discuss, in detail, how the chemical environment inside the canister (Eh, pH, pCO_2 etc.) affects the dissolution rate. According to Grambow's analysis, the radiolysis reactions dominate in the beginning to such an extent that the impact from the chemical environment is minor. However, as the radiation field around the fuel decreases, it can be expected that the importance of the chemical environment will increase, and this is why its evolution must be evaluated in the safety assessment. The importance of trace elements and the mass transport in the canister are additional uncertainties that may have to be taken into account in future safety assessments. To summarize, these uncertainties justify questioning whether it is at all possible to propose a realistic fuel dissolution rate in the way that it is done in SR 97. According to Grambow, with present-day knowledge, it would have been more reasonable to use a conservative dissolution rate which, however, does not necessarily need to be instantaneous.

The treatment of rapid radionuclide release from spent nuclear fuel upon contact with the groundwater has been handled in a highly simplified manner in SR 97. In the authorities' opinion, there are several good reasons to apply the simplified assumption that both release from grain boundaries and metal components occur completely instantaneously. However, it could be maintained that this is not consistent with the explicit objective to include both realistic and conservative cases in SR 97. It should be possible to report parts of the IRF separately (radionuclides in the gap, grain boundaries and metal components). Furthermore, it would have been simpler in that case to evaluate the data and compare with other studies. In general terms, there is good agreement with the shares proposed by SKB and those adopted in an EU project concerning safety in connection with the final disposal of spent nuclear fuel (Baudoin et al., 2000). However, Grambow proposes that the contribution from the ε phases and particularly the inventories of technetium should be further evaluated.

The authorities agree with Grambow that the results from SKB's spent fuel dissolution model must be considered to be inadequately documented for the results to be directly useful in supporting a consequence analysis. In order to maintain a high credibility for models and calculations, it must be possible to evaluate the quality of the experimental data and the conceptual uncertainties. Conceptual uncertainties can have a considerable impact when experimental data are extrapolated to very long time periods. Since whether or not the knowledge base is adequate can be called into question, the authorities consider that SKB in SR 97 should have used more robust assumptions to estimate an upper boundary for the fuel dissolution rate.

For such a complex area as spent fuel, it should be important to make optimum use of all known information on the fuel properties. Consequently, it is surprising that SKB does not devote more attention in SR 97 to the results from the extensive and costly spent fuel experiments carried out at Studsvik's Hot Cell Laboratory.

2.3.7 Hydraulic Analysis of Aberg, Beberg and Ceberg

The purpose of the detailed hydraulic modelling of Aberg, Beberg and Ceberg in SR 97 is to develop the hydraulic parameters needed as input data for the calculations of radionuclide transport in the canister defect scenario. The modelling is based on the assumption that the future groundwater flow conditions are the same as those today with the exception of certain known trends as land uplift.

For each site, SKB has developed a detailed hydrogeological model based on the geological structure models. The models have then been used to calculate the groundwater flow, transport paths and travel times from the hypothetical repository to the biosphere. The boundary conditions for the detailed flow models have been prepared on the basis of the regional model calculations reported in the base scenario. For each site, a base case is reported along with a number of variants which show how different model uncertainties affect the results.

The analyses of the hydraulic evolution of the different sites for the canister defect scenario represent an extensive task which is generally well documented in SR 97 and the background reports. In the authorities' opinion, the "Data and Data Uncertainties", and other background reports (such as Saksa and Nummela, 1998) contain a useful discussion of different types of models and parameter uncertainties that can affect the calculation results. However, in the authorities' opinion, there are deficiencies in how these discussions are followed up in the Main Report, for example, with respect to the justification of the choice of conceptual models and possible interpretations of data, as illustrated below.

The overall evaluation of the authorities is nevertheless that SKB's analyses of the hydraulic evolution of the site is adequate for the purpose of SR 97, namely to identify adequate parameter intervals for the flows and travel times as input data to the calculations of radionuclide transport.

Choice of Models for the Modelling of the Groundwater Flow

The authorities do not consider that SKB has, in a credible manner, shown that the main model that it has used, HYDRASTAR, is suitable to describe groundwater flow on a local scale in fractured crystalline bedrock. Several of the basic conceptual uncertainties reported in "Data and Data Uncertainties" and other SKB reports (such as Skagius et al., 1995, p. C-4 and C-5) are overlooked when the confidence in HYDRASTAR is discussed in the main report (Section 11.9.3).

HYDRASTAR is a stochastic continuum model that handles the natural distribution in the hydraulic conductivity of the rock by generating multiple realizations of the flow field. SKI's consultants, Geier and Voss (SKI, 2000c) each provide several examples of uncertainties and possible sources of error that, in the opinion of the authorities, should be taken into account in a better manner in the evaluation of the validity of the model result.

Geier points out that several scientific studies question the simplifications made in HYDRASTAR, including the assumption that the groundwater flow in fractured rock can be described as a porous medium using Darcy's law. Furthermore he states that previous calculations with a discrete fracture network model for Aberg and Beberg indicate that the assumption about a continuous medium is not applicable to the block sizes that are used in the HYDRASTAR model and for the modelling of the flow around individual deposition holes. Voss questions the value of the calculated flow distributions taking into account the arbitrary assumptions of distributions and spatial correlation structures for the hydraulic conductivity of the rock.

Use of Alternative Models

As an argument for the suitability of HYDRASTAR, SKB cites two studies, namely the Alternative Model Project (AMP) and a previous HYDRASTAR modelling of field experiments at Aberg.

The AMP was conducted to analyze conceptual uncertainties in groundwater flow modelling. Three different conceptual models were applied and compared from Aberg: (1) the stochastic continuum model, HYDRASTAR, (2) a discrete fracture network model, FracMan and (3) a channel network model, CHAN3D.

The authorities share the opinion of the IRT (SKI, 2000a) and several of SKI's consultants (SKI, 2000c) that this work is laudable. However, the authorities do not consider that the results from the AMP is an adequate basis for choosing HYDRASTAR as the single main model for all three sites, for the following reasons:

- The evaluation of the alternative models is very limited with respect to parameter uncertainties and conceptual uncertainties in the alternative flow models – major differences can be expected for more pessimistic calculation cases.

- The model comparison has only been conducted for Aberg – major differences between the models can be expected for Beberg and Ceberg which are less fractured and thereby less suitable for stochastic continuum description as in HYDRASTAR.
- The differences between the different models are greater than would seem in the Main Report. For example, almost all of the flows for the DFN model are higher than the median flow for the HYDRASTAR model. Furthermore, the calculated distributions are different, taking into account the share of very high flows and rapid transport paths in each model.

The second study that is cited as an argument for choosing HYDRASTAR as a main model concerns an inverse modelling of a large-scale combined pump and tracer element experiment at Aberg. The authorities agree with Geier that this modelling exercise gives very limited information on HYDRASTAR's suitability to describe the groundwater flow and transport paths in crystalline bedrock.

To summarize, the authorities recommend that SKB, in its further work on site investigations and safety assessments, should plan to make better use of the available modelling tools in the form of alternative conceptual models for groundwater flow. By testing alternative models, not only will the credibility of the flow-related data that are needed for the safety assessment increase but the application of the models will also provide vital information on which data should be measured and this will therefore improve the possibility of guiding the site investigations.

Any future decision to choose a particular conceptual model for the modelling of groundwater flow should, in the opinion of the authorities, be based on a significantly more thorough evaluation of the credibility of different models and an analysis of other advantages and disadvantages such as the possibility of using different types of site investigation data.

Representation of Small-scale Fracture Zones
Several of SKI's consultants (SKI, 2000c) criticize the simplified description of rock homogeneity in SKB's main model for groundwater flow (HYDRASTAR). Glynn and Geier each question the fact that the flow models do not take into account small-scale fractures and fracture zones (with a length scale of 0 – 100 m). In the opinion of the consultants, these structures could probably be as important as large fracture zones, especially in the analysis of flow paths in the rock between the repository and surrounding fracture zones. Geier questions whether it is at all possible to describe small-scale fractures and fracture zones with the application of HYDRASTAR used in SR 97. Tsang and Geier each express the opinion that SKB far too lightly dismisses the hydraulic importance of boreholes, rock bolt holes and plugs. In a long-term perspective, the possibility that these holes will become conductive and will short-circuit existing fracture zones cannot be excluded.

The authorities agree with the consultant that there are deficiencies in SKB's handling of small-scale heterogeneity and that this partly reflects limitations in the HYDRASTAR model. However, the level of ambition is considered to be acceptable taking into account the purpose of SR 97 and the limited quantity of data at repository depth for Beberg and Ceberg, in particular. Nevertheless, the authorities recommend that SKB should review its strategy for handling heterogeneity on different scales in the flow models prior to future site investigation work.

Formulation of Variants and Uncertainty Analysis
For each site, SKB has formulated a base case and a number of model and parameter variants to show the impact of different uncertainties on the calculated fluxes and travel times. To perform a meaningful evaluation of the completeness of the uncertainty analysis, the authorities consider that it is necessary to also describe the criteria used in the formulation of variants, who has participated in the decisions etc. To state, as SKB does in SR 97, that the variants are based on expert judgement without any further reference is inadequate.

One important result from the hydraulic analysis is that the flux and travel time distribution caused by the natural variability of the rock is comparable with the effect of the analyzed variants. The authorities share the view of Geier as well as Voss (SKI, 2000c) that this result could be due to the possibility that the chosen variants do not adequately reflect the uncertainties in the geological structural models and other hydraulic data.

Comparison between Sites
Based on the hydraulic analyses, SKB states that Ceberg has the longest travel times and the lowest fluxes. Aberg and Beberg have higher fluxes and shorter travel times while the distribution is largest in the case of Aberg. The authorities agree with SKB that caution should be exercised in drawing too far-reaching conclusions from these results bearing in mind the varying quality of site investigation data and the fact that only one conceptual flow model (HYDRASTAR) has been used for all three sites.

2.3.8 Radionuclide Turnover in the Biosphere

SKB presents the dose calculations by dividing the biosphere into a number of typical ecosystems and by using an ecosystem-specific dose conversion factor (EDF). In dividing the biosphere, the ground surface is divided into sub-compartments and each sub-compartment is associated with the typical ecosystem that is expected to result in the highest dose to man. The typical ecosystems are a peat bog, well, agricultural land, a lake, river and coastal region. The EDF values are calculated for each ecosystem and radionuclide. They are specified in Sievert per Becquerel (Sv/Bq) and summarize the results of model calculations from the time that a radionuclide enters the biosphere (Bq), is dispersed in the biosphere and finally, via different exposure pathways, results in a radiation dose to man (Sv). The principle of calculating EDF values is used in other contexts, such as for calculating dose consequences from releases from nuclear facilities and the principle has also been applied internationally.

In the opinion of the IRT (SKI, 2000a), SKB has developed a flexible method of biosphere modelling which is more developed than the methods used in several other safety assessments that have been performed. This means that the spatial variation of different ecosystems within the regions that can be affected by radionuclides from the repository is taken into account. At the same time, the IRT states that SKB has not shown that the new approach results in any other estimated consequences to man than those that would have been obtained by simpler models. The new method may be important in determining the impact on the environment on the basis of the radionuclide concentration in the biosphere. The IRT also raises issues such as the role that biosphere modelling should have in a long-term perspective and the role that the present-day biosphere should have in site selection when surface contamination is only expected to occur several thousands of years into the future.

The authorities' overall evaluation is that SKB's treatment of radionuclide turnover in the biosphere marks considerable progress. Typical ecosystems have been introduced, specific factors have been identified for the description of radionuclide transport in the biosphere. The most important comments of the authorities concern the following points:

- the transition between the geosphere and biosphere and the choice of typical ecosystems
- conservatism, completeness and uncertainties in calculating the EDF values

Detailed comments on these points are presented below.

Choice of Typical Ecosystems and Transition between the Geosphere and Biosphere
Nordlinder et al. (1999) present a classification of the biosphere for the three sites – Aberg, Beberg and Ceberg. The ground surface is divided into compartments of 250 m x 250 m and each compartment is associated with a typical ecosystem. SKB's method of dividing up and structuring the biosphere makes the safety assessment more universal and realistic and improves the credibility.

However, the way in which typical ecosystems are combined at a site may be artificial to some extent. It is not necessarily correct that the estimated release points from the geosphere (30 meters below the ground surface) correspond geographically to the outflow points in the biosphere. One possible alternative is that the affected areas should be identified from geosphere calculations and that the different typical ecosystems are then assumed to cover these surfaces.

SKB states that the similarities between the EDF values for different radionuclides presented in Figure 9-24 in the Main Report are due to the fact that varying dilution is the factor that mostly separates the type ecosystems from each other and that this factor affects all radionuclides equally. From the description of the models used, it is evident that dilution volumes and areas have been given arbitrary values with the purpose of being conservative. It is not clear whether the observed differences in EDF values between the typical ecosystems also reflect different degrees of conservatism for different ecosystems. This indicates the importance of a more realistic description of the transition between the geosphere and biosphere, which would improve the estimates of volumes/areas.

The uncertainty analysis shows that the volume or area of the recipient in the biosphere can affect the calculation results. Since the radionuclides enter directly into the biosphere, an assumption must also be made regarding the size of the area or volume concerned. The uncertainties that are related with this procedure indicate that the processes that describe the interface between the geosphere and the biosphere should be studied further.

With the exception of the lack of an explicit treatment of the forest ecosystem, the typical ecosystems modelled seem to be adequate to describe the possible biosphere types of today and probably of the future. However, two comments can be made regarding the choice:

1. The well should be seen as an exposure pathway rather than as a separate typical ecosystem. Instead this exposure pathway can be included as part of a typical ecosystem, especially with respect to agricultural land and peat-based ecosystems (the issue of mixed exposure pathways is raised in Section 4.3.6).

2. The assumption that peat bogs can be seen as a pessimistic description of forest is not obvious and must be justified. There is a considerable difference between radionuclide migration in a forest ecosystem compared with that in a peat bog and the exposure pathways to man are different in these two ecosystems. Furthermore, forest can be expected to be the dominant ecosystem and should therefore be included as a typical ecosystem, which SKB has also acknowledged.

Conservatism, Completeness and Uncertainties in the EDF

As mentioned above, in order calculate the radiation doses to man, SKB has introduced ecosystem-specific dose conversion factors (EDF). This approach is normal. However, there is reason to further study and describe the information value provided by these factors. The information value is affected by the conservatism of the EDF values, and by the degree to which the conservatism differs for different radionuclides and ecosystems. Similarly, in a safety assessment, it must be clear which fluxes and concentrations function as “intermediaries” in the calculation of the EDF values, since these values are the basis for judging the relevance of alternative exposure pathways and alternative protection targets (cf. health protection and environmental protection).

The processes affecting radionuclide transport from outflow points in the geosphere to typical ecosystems have not been modelled. This means that the retention in saturated and in unsaturated soil and other factors have not been taken into account. This is probably a conservative approach, but the degree of conservatism may be different for different radionuclides. Similarly, the way in which the radionuclides enter a certain ecosystem may determine their distribution in the ecosystem. Radionuclides can reach an inland lake via the sediment and be retained there. In this case, the concentration of certain radionuclides in the sediment may be higher than if they were to directly attain the water phase. In connection with land uplift, the higher concentrations in the sediment may result in higher radiation doses to man.

SKB assumes that the radionuclide concentrations in the well water are inversely proportional to the well capacity. The intention behind this assumption is to obtain conservative calculations. However, no mention is made of the degree of conservatism. From work underlying the analysis, Bergström et al. (1999), it can be seen that the well capacity is equal to the water consumption per unit of time. This consumption can, but does not necessarily have to be equal to the flow of radioactive substances in the well.

This affects the degree of conservatism in the calculated radionuclide concentrations in the well water. No explanation is given of why the radionuclide retention in the surface-near groundwater has been taken into account nor of the extent to which this implicit assumption is conservative.

The authorities are not convinced that peat moss is a more conservative ecosystem than the forest ecosystem. Furthermore, the forest can be assumed to be a dominant ecosystem and should therefore be included among the ecosystems modelled by SKB. Development work on the forest ecosystem is currently in progress within the IAEA BIOMASS programme.

The EDF factors are based on a continual radionuclide release over a period of 10,000 years. One issue that warrants further discussion is the consequences of (the implicit) assumption of a constant biosphere over a time period of 10,000 years. Radiation doses as a result of external exposure in the coastal area have not been taken into account and the justification for this should have been provided.

The models for the well, lake, river and agricultural land are not described in the Main Report. The following comments concerning these models are based on Bergström et al. (1999).

- It is unclear why external exposure of man has not been taken into account for the lake model. In the case of several model parameters, the lowest and highest values have been set at 90 and 110 % of the mean values, but no explanation is provided.

- The river model is the same as that for the well, but with another assumption regarding the water flow. The postulated flows for the well and river are 2,000 m^3/year and 5,000,000 m^3/year, respectively. The comments provided above with respect to dilution in the well are also applicable to the river. The importance of the runoff area and runoff is unclear. The proposed parameter intervals are probably too small. The product of these is equal to the flow in the river water, which probably has a much larger variation interval.

- The model for agricultural land describes a saturated zone with an almost horizontal groundwater flow and with a water level about one meter below the ground surface. No explanation is given of how the groundwater level is chosen and how this chosen parameter value affects the calculation results. SKB states that root uptake is one of the processes allowing radionuclides to reach the surface layer. However, it is not clear from the description in the report, whether root uptake is included in the mathematical model or what impact it would have if it is not included. It is unclear exactly what the other flow represents that is included, in addition to runoff, in the equation for transfer rates from deep earth to the saturated zone.

- If the flows are diluted within an arbitrarily chosen area, the concentrations of radioactive substances will also be arbitrary. In the case of most of the model parameters, the variation interval is too small to adequately represent all possible situations.

SKB states that the greatest uncertainties lie in the identification of the typical ecosystems that are relevant. Bearing in mind the long time-scale, it is almost impossible to predict which ecosystem will predominate within an area. Consequently, it may have to be shown that the repository is safe for all postulated ecosystems. This also means that the uncertainty in the choice of ecosystem does not have to be considered in the same way. However, the uncertainty in the estimates within an ecosystem must still be determined. Furthermore, according to SSI's regulations (SSI, 1999), an estimate based on currently known conditions and ongoing known changes must be made for the first thousand years. This probably limits the range of possible alternatives, at the same time that it increases the requirements on precision and relevance for the short-term time-frame.

2.3.9 Models for Radionuclide Transport and Consequence Calculations

In SR 97, radionuclide transport calculations were performed using the COMP23, FARF31 and BIO42 model chain. COMP23 comprises the near field which includes the canister, buffer, backfill and surrounding rock. FARF31 comprises the far field in the rock up to the biosphere. BIO42 consists only of conversion factors (EDF) that have been calculated for different biospheres and which convert a given release (Bq) into a dose (Sv).

In addition to the models that are directly included in the calculation chain, certain underlying models are of very great importance for the dose and risk estimate obtained. Particularly important examples are the groundwater modelling that SKB has largely conducted with HYDRASTAR and the model used in SR 97 for a defective canister which indicates a long delay time before radionuclide transport actually occurs. The models for fuel dissolution and solubility estimates are also examples of important data for radionuclide transport calculations. Detailed comments on the underlying models are presented in sections 2.3.5-2.3.7 of this appendix.

In general, the authorities consider that, prior to SR 97, SKB has developed an appropriate selection of models that correspond to the level of ambition that can be expected at this stage. However, the description of the models' limitations and uncertainties can be improved. Even if the authorities, like SKB, consider that a strict validation is not possible for the type of model used in this context, the usefulness of the models in different contexts should be discussed in detail. This should be done in connection with the model description, so that those using and evaluating the models can judge their validity and limitations. To improve the credibility of SKB's analysis tools, it should be possible, in the future, to identify and document limitations and deficiencies in the models included in SR 97. Suitable approaches could be to use alternative conceptualizations or models with a higher resolution for a specific aspect.

In the authorities' opinion, there are advantages in using, as in SR 97, supplementary models with varying complexity and degrees of detail adapted to different purposes along with, for example, relatively simple and robust models for dose and risk estimates. In the authorities' view, it is very important that SKB should, in the future, study and document the simplification errors that always exist for models for consequence calculations (such as COMP23 and FARF31). These can have a considerable impact on the final result and can, for example, be associated with highly simplified boundary conditions, representation of heterogeneous media, reduction of dimensionality and the use of collective parameters to represent entire groups of processes.

With respect to the underlying models, the authorities have observed a certain discrepancy between the efforts put into understanding the model limitations for different areas. For example, the hydrology modelling is generally more thorough than the near field modelling. In the authorities' opinion, the models for the evolution of the near field are based on too limited data, in certain cases the result of one-off efforts. Since the results obtained are often directly applied to the consequence calculations, there must be considerable confidence in the models. For example, the models for the evolution of a canister and fuel dissolution appear to be inadequately investigated and documented. Since the near field is of considerable importance for overall safety in SR 97, there is reason in future to try to ensure that the different parts of the safety assessment have a more comparable level of ambition and a degree of detail which reflects their role in demonstrating the overall safety.

Several of the external reviewers praise SKB for the indepth discussion on premises (such as conceptual model uncertainties) and input data for the hydrogeological models. At the same time, the reviewers consider that a similar discussion should have been presented for the simplified transport model (FARF31) that is included in the calculation chain for the consequence analysis. In the opinion of SKI's consultant, Tsang (SKI, 2000c), the uncertainties in the simplified transport models should be illustrated through comparisons with more detailed process models for different transport processes.

Wörman and Xu (SKI, 2000c) discuss the importance of different types of conceptual faults in radionuclide transport models, and maintain that the importance of a certain parameter depends on how the transport processes are described in the calculation models. Wörman and Xu show that the maximum penetration depth for radionuclide diffusion in microfractures in the rock can have a greater impact on the calculation results than reflected in SR 97. Wörman and Xu also consider that a detailed investigation of how sorption kinetics affect the choice of effective parameters may be warranted.

In the IRT's opinion (SKI, 2000a), SKB has an appropriate selection of models and calculation tools for the needs of the safety assessment. However, the IRT considers that the documentation of conceptual assumptions, mathematical formulations and the scientific support for the selected models should be improved. The purpose of the documentation is to improve traceability and transparency in SKB's model selection and to clarify the role of different models in the safety assessment.

COMP 23

In the opinion of the IRT, the information presented concerning work carried out with COMP23 is unclear. A description of how verification, quality assurance and validation were handled should have been presented. One particular problem that must be resolved is the fact that the code appears to represent a mixture of theoretical and empirical equations.

SKB has chosen to, in COMP 23, describe four possible transport pathways from the canister (cases Q1-Q4). Case Q4 describes transport through the buffer into the geosphere via diffusion (2.5 m) through the rock in a postulated fracture zone. A variant of Q4 can be defined if the diffusion-driven transport in the rock is replaced by transport in a fracture. This variant is important since it will probably be difficult to exactly determine the beginning and end of a diffuse fracture zone. If it cannot be excluded that the fracture zone is so close to the canister that diffusion in the rock is worth investigating, as it is in case Q4, the occurrence of a direct flow path between the canister position and fracture zone should be investigated.

The calculated specific groundwater fluxes in the HYDRASTAR hydrology model represent the mean value over blocks that are about 30,000 m^3 in size and, therefore, provide no detailed information on the flow in the different transport pathways that are assumed in COMP23. To obtain relevant flow data for COMP23, SKB has been forced to conduct more or less arbitrary upscaling of the calculated flows in HYDRASTAR. In the authorities' opinion, in future work, SKB should develop near field models so as to avoid this type of conceptual simplification. The authorities also share the opinion of Voss (SKI, 2000c) that SKB in SR 97 should at least have conducted a sensitivity analysis to illustrate how these uncertainties affect the estimated transport of radio-nuclides out of the near field.

FARF31

As previously indicated, several of the reviewing bodies consider that the importance of simplification errors has not been described in adequate depth. In the opinion of Geier (SKI, 2000c), the fact that variable flow porosity cannot be handled may be a limitation. A further limitation in performing calculations with FARF31 in its existing form is that the Peclet number must be kept constant.

2.3.10 Data for Radionuclide Transport and Consequence Calculations

Input data for radionuclide transport calculations are reported in detail in the background report "Data and Data Uncertainties" and summarized in SR 97 (canister defect scenario). In the authorities' opinion, SKB's systematic account of selected data and discussion of data uncertainties is laudable. However, the authorities share the opinion of the IRT and several of SKI's consultants and reviewing bodies that there are deficiencies in SKB's strategy for selecting parameter values and distributions and in the reporting of the expert judgements upon which the parameter values are based. These are discussed below. Comments on individual parameter values are presented in Sections 2.3.1-2.3.8 of this appendix.

Data Selection Procedure

The background report, "Data and Data Uncertainties" contains a good discussion of the scientific basis for the selection of different parameters. On the other hand, the description of the procedure for selecting parameter values and distributions for calculations is unclear and deficient, which is emphasized by the unanimous opinions of the IRT (SKI, 2000a), SKI's consultants, Wilmer and Crawford, Tsang, Wörman and Xu (SKI, 2000c) and Pereira (SKI, 2000b). The problem is that, as a rule, it is not clear how the judgements have been made and how different experts have contributed to the judgements, resulting in inadequate traceability.

Furthermore, the IRT would like to see the broader involvement of experts from different scientific disciplines in the data selection. Tsang proposes that SKB should consider formal procedures for expert elicitation of the type used in the nuclear waste programmes in England and the USA (Nirex, 1995 and DOE, 1997).

The authorities agree with the criticism of the IRT and recommend that SKB use well-defined procedures that have been subjected to quality assurance for the formulation and documentation of expert judgements in its future safety assessments. This particularly applies to parameters that are difficult to establish and parameters with a considerable impact on calculation results, such as the size and frequency of initial canister damage and certain transport parameters (flow-wetted surface, distribution coefficients and penetration depth).

Completeness and Balance in Data Handling

In the opinion of the IRT and several of SKI's consultants, the treatment of data and data uncertainties is unbalanced. The conditions for the hydrogeological input data are, for example, very well documented, while uncertainties and data used in the transport models are more generally treated. Furthermore, in the view of the IRT, Wörman and Xu (SKI, 2000c) and Pereira (SKI, 2000b), the detailed discussion on data and data uncertainties should comprise all scenarios and not just be limited to the canister defect scenario as is the case in SR 97.

In the opinion of Wörman and Xu as well as Pereira, SKB has not shown, in a satisfactory manner, that pessimistically selected parameter values can compensate for uncertainties in the simplified transport models. Wörman and Xu propose that SKB should develop a more comprehensive dataset that will enable evaluations to be made with alternative models for important processes such as sorption, matrix diffusion and colloidal transport.

The authorities share the opinion of the IRT and the consultants that SKB should develop a dataset with a more even level of ambition for all analyzed scenarios in the safety assessment. The authorities also recommend that SKB should improve its description of the conceptual uncertainties associated with the selected transport calculation models.

Input Data for Probabilistic Calculations

SSI's regulations (SSI, 1999) require that the consequences of the repository should be described in the form of risk. Consequently, in SR 97, probabilistic calculations are performed of radionuclide transport and migration from the repository. As a basis for the calculations, SKB has used continuous distributions to describe uncertainties (or spatial variability) for flow-related data (groundwater flow and travel times). For other input data, the data uncertainties are quantified using bimodal distributions of a reasonable value which is given a probability of 90 % and a pessimistic value with a probability of 10 %. SKB states that continuous probability distributions were not used for all parameters due to the uncertainty of the database.

The IRT (SKI, 2000a) and several of SKI's consultants (SKI, 2000c) question SKB's approach of using reasonable and pessimistic parameter values. The IRT states that the probabilistic uncertainty and sensitivity analyses are incomplete, since all possible parameter values are not taken into account in the calculations. Furthermore, the method of assuming a 90 % and 10 % probability for reasonable and pessimistic data, respectively, is not scientifically accepted, which makes the results of the probabilistic calculations difficult to interpret and possibly, misleading. As mentioned above, the selection of the reasonable and pessimistic parameter values also means that SKB has been forced to make arbitrary judgements which are not adequately documented, in many cases.

All of the external experts and reviewing bodies that have commented on SKB's risk calculations recommend that SKB should use a less arbitrary method of quantifying parameter uncertainty, based on continuous probability distributions. The experts do not consider that the fact that the database is inadequate for many parameters is a good enough reason to limit the analyzed parameter intervals in the way that this has been done in SR 97. The IRT and Pereira (SKI, 2000b) state that the database used as a basis for the probability distributions for many parameters, such as distribution coefficients, is no more deficient than the data used for the flow-related parameters. Wilmot and Crawford (SKI, 2000c) also specify the use of expert elicitation as a means of characterizing parameter uncertainty and probability distributions.

Pessimistic and Realistic Approach

An important aspect of data selection is naturally the real purpose of the calculations where data are utilized. Conservatism must be applied in selecting data and models for the final calculations in the safety assessment that will demonstrate the compliance of safety with SSI's radiation protection criteria. It is naturally a decisive factor that optimistic results can be avoided as a result of unavoidable deficiencies in the database and conceptual understanding. To ensure that this is not the case, the significance of the uncertainties must be taken into account in the choice of both pessimistic and realistic data. On the other hand, if the purpose is to increase the understanding of and insight into how the repository can be affected by different factors, the database can, instead, focus more on using the most probable data, which also includes the optimistic part of a certain database.

In the authorities' opinion, this type of consideration should be clearly reported in order to facilitate the evaluation of the justification for the use of the database. The IRT (SKI, 2000a) states that the quantitative results from SR 97 are probably of limited use in supporting site characterization or design studies. The authorities partly agree with this conclusion, but consider that SKB probably has access to the necessary tools for developing more purely realistic calculation cases than could be used for this purpose.

The same line of reasoning concerning conservatism or realism can also be applied to the selection of models. Detailed models can provide support for simple conservative models and can also provide feedback for research, site investigations etc. However, they should not be used as a direct basis for consequence calculations if it cannot be shown that the conceptual uncertainties are small (see also Section 2.3.9 of this appendix).

To summarize, in the authorities' opinion, "Data and Data Uncertainties" provides a deficient basis for the probabilistic calculations in SR 97 and this reflects the lack of a deliberate strategy for the selection of data and for conducting risk analysis. This can partly be explained by the fact that the risk analysis was introduced at a late stage into SKB's work on SR 97, as a result of SSI's new regulations. The authorities recommend that SKB should review the need of data for its further development work on risk analysis and probabilistic calculations. The possible impact of how the above deficiencies in data handling could affect the results of the probabilistic calculations in SR 97 is discussed further in Section 2.3.11 of this appendix.

2.3.11 Calculation Cases

SKB presents a number of calculation cases for the canister defect scenario, based on the transport and migration-related processes identified in SR 97 (Chapter 9.9 and 9.10). The purpose of the calculations is to quantitatively describe radionuclide transport for the canister defect scenario, describe the significance of uncertainties in the input data, compare the estimated risk for the three repository sites with SSI's acceptance criteria and illustrate the importance of each barrier in the repository system. Based on these purposes, SKB presents a number of calculation cases:

- Reasonable case: deterministic calculations performed for the three repository sites, assuming that an initial canister defect after 200,000 years grows so that a continuous water path to the fuel is formed. "Reasonable" values are selected for all input data.
- Uncertainty analyses: deterministic calculations for which the values in one parameter group at a time are replaced from reasonable to pessimistic. This illustrates the sensitivity of the models and the interval between reasonable and pessimistic values.
- Special cases: deterministic calculations that show the effects of the elimination of a safety function.
- Risk calculations: probabilistic calculations for the three repository sites which illustrate the probability of a certain consequence occurring.

In the authorities' opinion, SKB, in its canister defect scenario, includes a comprehensive set of calculation cases that combined have good prospects of illustrating the possible consequences of a defective canister and of creating an understanding of the interaction of the different functions of the system. The calculation cases provide a reasonable coverage of the comments expressed in SKI's draft of general recommendations, even if the sensitivity and uncertainty analyses must be reinforced. Below, the authorities present certain proposals for improvements and modifications of calculation cases for future safety assessments.

Reasonable Cases
In the authorities' opinion, the reasonable cases are primarily a starting point for uncertainty and risk calculations as well as comparisons with Aberg, Beberg and Ceberg. It should be pointed out that these cases should not claim to be more realistic than the other deterministic cases. This is due to the fact that they do not explicitly take into account parameter variability, which is an inherent characteristic of several of the most important parameters, such as groundwater flow.

Uncertainty and Sensitivity Analyses
SKB has performed a sensitivity analysis on the basis of calculations performed for the "reasonable case" for Aberg, Beberg and Ceberg. The analysis was conducted by postulating pessimistic input data values for different parameters/parameter groups, at the same time that reasonable values are assigned to other data. The parameter groups that SKB has chosen to analyze are:
- canister-related data
- fuel-related data
- sorption data in the buffer and backfill
- data related to the interface between the buffer and the rock
- chemical transport data in the geosphere
- flow-related transport data in the geosphere
- biosphere data.

SKB's sensitivity data show that the greatest impact on the calculated dose at Aberg is obtained for the number of initially defective canisters, the F factor (the product between the advective travel time and the flow-wetted surface) and the dose factors in the biosphere (EDF values). According to Figure 9-41, other parameters have a relatively low impact.

Uncertainty and sensitivity analyses can, if they are presented in a pedagogical manner, aid the understanding of how the repository system can be affected by different factors. In the opinion of the authorities, the calculation cases that SKB presents provides valuable insight into how certain parameter groups affect the transport of the different radionuclides studied. SKB's result indicates that the prospects for realizing the multiple-barrier concept are good, since none of the cases that have been discussed entail any decisive change in the end result. However, in the opinion of the authorities, definitive conclusions should not be drawn on the basis of these results. It should be taken into account that the simplified models for consequence analysis do not allow all aspects of radionuclide transport to be studied on the same level of detail and, therefore, the sensitivities obtained when different parameter groups are varied cannot simply be regarded as comparable. Consequently, in future SKB should describe comparisons with sensitivity analyses based on more detailed underlying models and relate the sensitivities to the abstraction and simplification errors that affect the consequence calculations (see Section 2.3.9 of this appendix).

In the authorities' opinion, SKB should aim to develop the uncertainty and sensitivity analyses so that they play a more important role in future safety assessments. Above all, more than one parameter or parameter group should be varied at the same time, since this would not only show the parameters but also the parameter combinations that are most important. In SR 97, SKB presents such multiple parameter variations to study the retardation in the geosphere with an analytical solution of a simple model. It could have been possible to perform similar calculations with the complete calculation chain. In this way, it would have been possible to obtain an overview of the relative importance of the barrier functions in the near and far field for the relative radionuclides. Furthermore, it would be possible to vary the parameters that are not specifically subjected to sensitivity analysis in the probabilistic framework that SKB has developed for risk analysis.

SR 97 does not contain a pure sensitivity analysis, even if a figure is provided that shows the relative change in maximum dose when a parameter is changed from realistic to pessimistic (Figure 9-41). Since the choice of parameter interval is, in itself, a significant uncertainty, which must be completely or partially based on subjective expert judgements, it would be desirable to include an analysis that separates the effects of the sensitivity and size of the parameter interval. Such an analysis should also take into account the possibility that model sensitivity can vary for different parts of the parameter area. These aspects can be studied if the effects of a constant change of input data are calculated, in percentages, for different systematic input data choices and for all parameters.

Special Cases

To study the importance of the different barriers in the canister defect scenario and as a complement to the sensitivity analysis, SKB also performs calculations for a number of special cases (what-if calculations):

- the fuel is completely dissolved when a continuous water path arises
- the radionuclides have no solubility limitations
- major initial canister defect
- the bentonite diffusion resistance is neglected
- geosphere retention is neglected.

SKB's choice of special cases is based on extreme assumptions concerning failure functions of individual barrier functions, at the same time that other barrier functions are assumed to perform as intended and are calculated with the reasonable parameters.

In the authorities' opinion, the special cases are a valuable complement to the uncertainty analysis and further illustrate the KBS-3 method's prospects of realizing the multiple-barrier principle. SKB states that none of the included cases exceeds the dose limit used by SKB (apart from Ra-226 in the case of no solubility limitations). In this context, the authorities point out that there are no requirements whatsoever that a certain dose limit must be respected in these cases. The calculations are only illustrative and can, on the contrary, be very valuable in investigating whether any combination of parameters can have a major impact, regardless of whether such a combination is less probable or improbable.

As with uncertainty analysis, there is a risk that the meaning of certain barrier functions will be underestimated when the uncertainty of the other parameter values used for the other parameter functions are not taken into account. For example, SR 97 states that the fuel dissolution rate has a small impact on the overall performance of the barrier system. However, the opposite could also apply, namely that the solubility limitations have a small impact since the dissolution rate is slow enough. It is obvious that, as a whole, this line of reasoning gives a misleading view of the importance of the barrier functions. It should therefore be important to also take into account combinations of different parameter groups at the same time and to, for example, investigate the importance of the dissolution rate for a conservative choice of solubility data.

Risk Analyses

In SR 97, SKB presents risk analyses for Aberg, Beberg and Ceberg with either peat bog or a well as the exposure pathway. Correlated distributions are used for advective travel times and flows while pessimistic values are used for delay times, fracture geometry in the near field, Peclet number and maximum penetration depth in the rock matrix. For other values, a bimodal distribution is used with the probabilities of 0.9 and 0.1 for reasonable and for pessimistic data, respectively.

In the opinion of the authorities, SKB's risk analysis is a good first step in the attempt to show compliance with SSI's risk criterion. However, the authorities consider, as does the IRT (SKI, 2000a), that the risk analysis must be developed prior to future safety assessments, for example with respect to the statistical treatment of parameter values, the weighing together of different scenarios and the content of the risk analysis.

In the authorities' opinion, SKB has not clearly shown that the distribution of 0.9 and 0.1 between reasonable and pessimistic data is a conservative choice. This choice has a considerable impact on the realistic data and a significant share of the uncertainties for this case must be taken into account already during the selection of realistic data. It is unclear whether this is the case, for example for the fuel dissolution rate. Furthermore, it must be considered to be obvious that the uncertainties in the choice of reasonable values are greater for certain parameters than for others. Therefore, it would have probably been justifiable to evaluate the parameter groups one at a time.

In the opinion of the IRT and of SKI's consultants, Wilmot and Crawford (SKI, 2000c), SKB has not clearly justified its strategy for data selection in connection with the risk calculations. In the opinion of the authorities, the representation of many parameters with only two values would probably limit the validity and statistical significance of the analysis. In the opinion of Pereira (SKI, 2000b), the steep part of the CDF curves presented by SKB (Figures 9.43-9.45) could be an artefact from the use of bimodal distributions, rather than a sign of the "robustness" of the repository concept. In the authorities' opinion, SKB should, for each parameter group, evaluate the type of distribution that can best represent known data and their uncertainties. If there is little statistical data, constant distributions can, for example, be used to stretch out the uncertainties and obtain a reasonable outcome for values far from the middle of the distribution. Taking into account Pereira's comments and SKB's conclusions concerning the robustness of the system, it is important to investigate how the choice of distribution (bimodal, constant, log-normal etc.) affects the form of the CDF curve.

In the risk calculations, SKB has not taken into account the correlations between input parameters (apart from that between the flow and advective travel times) and justifies this by stating that this procedure is probably conservative. In the authorities' opinion, this issue warrants further investigation, since it cannot be excluded that correlations exist that degrade the repository's performance, for example if rapid flows were to be correlated with low chemical retardation.

In the authorities' opinion, SKB should consider whether alternative or supplementary ways of presenting risk calculations could improve the overview of the results. Wilmot and Crawford (SKI, 2000c) point out, for example, that it should be relevant to describe how the risk changes as a function of time. Other relevant detailed views relate to how SKB has decided when adequate conversion has been reached, which calculation method has been used and how SKB has justified the choice of radionuclides that do not need to be included in the risk calculations.

2.3.12 Discussion of Results

Based on the results presented in the canister defect scenario, SKB states that the repository system appears to have good prospects of complying with SSI's radiation protection requirements for Aberg, Beberg and Ceberg. Based on the review of the canister defect scenario, the authorities cannot identify any obvious difficulties that the proposed concept would have in complying with the required safety and radiation protection requirements. However, in the opinion of the authorities, it is too early to judge compliance with SSI's radiation protection requirements, since essential information is still lacking, for example, site data and data from canister and buffer manufacturing. The analysis presented in SR 97 should therefore primarily be viewed as a first step towards a final safety assessment.

The review of SR 97 has been somewhat difficult to carry out, partly because certain processes, the importance of which cannot be easily determined, have been eliminated from the safety assessment at an early stage and partly because the methodology for data handling and risk calculations is not yet fully developed. Furthermore, no explicit description of environmental protection aspects – required by SSI's regulations – is provided. In the authorities' opinion, SKB should be able to improve confidence in the repository system by more clearly illustrating the importance of the different barrier functions, such as by testing the system more stringently against various hypothetical calculation examples. A detailed review and judgement of the prospects of the repository system of complying with SSI's radiation protection criteria, based on a complete safety assessment, can only be conducted when detailed data are available from site investigations and when more extensive practical experience of the engineered barriers has been obtained. On the other hand, it may be appropriate for SKB to prepare a new safety assessment before these premises are fulfilled in order to document and evaluate progress with respect to risk calculation methodology, data handling and the development of new models for radionuclide transport.

The results from SR 97 agree somewhat well with the authorities' own calculations, presented in SITE-94 (SKI, 1996b) to the extent that the doses for a time-scale of several 100,000 years are completely dominated by radionuclides with a high solubility and poor geosphere retardation (primarily I-129). In SR 97, the calculated doses for

Aberg (reasonable case) is just over an order of magnitude lower than for the corresponding calculation in SITE-94. Bearing in mind the differences in calculation methodology as well as the fact that these doses are on very low levels, this comparison must be considered to be satisfactory. Both assessments (SR 97 and SITE-94) have in common the fact that none of the potentially most hazardous radionuclides, such as actinides, significantly contribute to the dose or risk. The possible conceptual uncertainties that can affect this conclusion should be a prioritized area prior to future safety assessments.

With respect to the time of the dose exposure, SKB's account indicates that this will only occur after 200,000 years (according to Figure 9-28 up to Figure 9-40 and Figure 9-46 up to Figure 9-50 apart from 9-32 and 9-48). This long delay is based on SKB's model for the evolution of a defective canister. Taking into account the uncertainties associated with this model (and discussed in Section 2.3.5 of this appendix), the authorities consider that the presentation in SR 97 is misleading in this respect. SKB's model is not an adequate basis for excluding the possibility of dose exposure before 200,000 years.

The comparison between Aberg, Beberg and Ceberg in SR 97 indicates significant differences with respect to radionuclide retardation in the geosphere. It is difficult for the authorities to judge whether these are due to actual differences or whether they can be explained by differences in the available data for the different sites. In spite of this, it is obvious that the groundwater flow and the length of the transport paths are important factors to take into account in site selection. However, it should be emphasized that radionuclide retardation is only one of several other important functions of the geosphere. The geochemical and mechanical premises for ensuring barrier integrity for hundreds of thousands of years is at least as important.

3 Climate Scenario

3.1 SKB's Report

For the very long time periods covered in SR 97, major climate changes are expected and their impact on the repository must therefore be analyzed. SKB's description of climatic conditions is based on three climate-driven process domains:

- temperate/boreal domain
- permafrost domain
- glacial domain

These domains are, in turn, divided into more detailed regimes. The climate-driven process domains and regimes are expected to present a general picture of the climate conditions and the extent of these conditions in time and space. In the climate scenario, SKB bases its radionuclide transport calculations on the assumption that the ice front is always directly above the repository. However, SKB points out that, in reality, the ice front is only directly above the repository for a limited period of time. High groundwater flows are expected to occur which means that there is a low advective transit time of the radionuclides to the biosphere. A major canister defect is assumed to occur after 20,000 years.

According to SR 97, the purpose of the climate scenario is to:

- show how climate changes can affect the isolating function of the engineered barriers
- show the consequences of the occurrence of one or more defective canisters during periods when the repository's retardation capability is impaired.

3.2 Comments by the Reviewing Bodies

The Geological Survey of Sweden (SGU) states that knowledge of climate changes as well as of the growth and melting of continental ice sheets is deficient and that climate changes caused by, for example, human actions (greenhouse effect) are not covered by the climate scenario presented in SR 97.

Mörner, Stockholm University, raises the issue of the impact of climate changes (ice ages) on the occurrence of major earthquakes (see also Appendix 2, Chapter 4 of this Review Report).

In the opinion of Pereira, Stockholm University, in spite of the fact that the climate scenario is well written, considerable model development work needs to be done, for example, the introduction of time-dependent parameters in the geosphere modelling.

3.3 SKI and SSI's Review and Evaluation

3.3.1 General Comments on the Climate Scenario

SKB presents a relatively extensive description of the basic mechanisms that determine climate changes and describes a possible climate evolution in Scandinavia over the next 150,000 years, based on different model calculations of future conditions. Descriptions of temperate/boreal, permafrost and glacial conditions are provided in general terms as well as in specific terms for the three repository sites, Aberg, Beberg and Ceberg. SKB also discusses the uncertainties in the description of boundary conditions.

The climate predictions for the climate scenario are based on astronomic factors, such as variations in the earth's orbit, the tilt of the axis of the earth and its wobble as well as a prediction for variations in the solar activity. The climate prediction comprises a hundred thousand-year scenario which is, in many respects, similar to past ones, which in the authorities' opinion, is a reasonable premise. The conversion of the astronomical variations into temperature data at the earth's surface is performed through i.a. regression analysis using proxy data for temperatures for the past 100,000 years.

Scenario Formulation
The climate scenario in SR 97 is based on extensive data that are presented in various parts of the Main Report, background reports and references. In the authorities' opinion, SKB should more clearly describe the judgements and compilations upon which the chosen climate evolution is based.

The authorities share the view of the International Review Team (IRT) (SKI, 2000a) that the importance of time-dependent processes must be better investigated in the safety assessment. SKB should also re-examine the delimitation between the climate scenario and the tectonics/earthquake scenario which, in certain respects are intimately connected to each other, for example, with respect to certain mechanical effects such as earthquakes in connection with the retreat of the ice sheet (see also Section 3.3.4 and Chapter 4 of this appendix).

Modelling of Climate Evolution
According to SKB, the climate scenario presented in SR 97 is a subjective compilation of results from the models and the evolution during the Weichsel period. To provide a geographical picture of the extent of the ice sheet at different times, a model has been used that calculated the shoreline displacement. To describe the extent of the different climate-driven process domains, another model has been used which simulates the Scandinavian continental ice sheet. In addition to this, a subjective judgement of the extent of permafrost was made, based on the above mentioned models and on present-day conditions in North America.

The authorities acknowledge that the models used for the climate predictions in SR 97 are internationally accepted. However, the authorities consider that they are overutilized in that too much confidence is placed in the results in the radionuclide transport calculations, for example. In the section dealing with calculations, there should have been a detailed discussion of the uncertainties in the assumptions made in the formulation of a possible climate sequence and how this affects the relevance of the calculation results.

The predicted evolution of the climate scenario is generally accepted, namely that there will be alternating cold and warm periods over the next hundred thousand years, like we have experienced during the last glacial cycle. However, knowledge of time and temperature conditions as well as details concerning the continental ice sheet growth and melting is deficient.

Furthermore, the authorities point out that different climate models give different results. This can be illustrated by a comparison of SR 97 with previous analyses (Figure 10-6 in SR 97, Figure 11 in Forsström, 1999, Figure 7.1a in King-Clayton et al., 1995 and discussions presented in Gascoyne, 1999). The results from these analyses indicate a significant distribution in what can be expected, for example, whether or not permafrost will exist, variations in permafrost depth and duration and variations in the extent of the ice sheet.

In the light of the above, the authorities' view is that SKB, in future safety assessments, should illustrate the importance of uncertainties in the climate predictions in a more complete manner, for example, by evaluating alternative climate evolutions. The climate scenario in SR 97 only represents one of several possible climate evolutions. The authorities also see a need for SKB to support its assumptions, to a greater extent, regarding quantitative analyses of how different climate regimes can affect repository performance.

Finally, the authorities consider that SKB's level of ambition has been relatively high in the formulation of the climate scenario in SR 97, but that there are a number of uncertainties in the assumptions that must be clarified in future safety assessments, for example, by discussing scenario uncertainties and by illustrating them by using sensitivity analyses.

3.3.2 Thermal Evolution

SKB states that freezing point is not reached at repository depth and that, therefore, no thermal impact is expected to occur in connection with climate changes. In the opinion of the authorities, the issue of permafrost depth and a possible impact on the repository must be supported by more exhaustive reasoning in future safety assessments, addressing for example how the groundwater flow is affected by permafrost even though the permafrost does not reach repository depth. There are significant uncertainties in the assumptions concerning the vertical temperature distribution and assumed basal temperature conditions below the ice (Holmlund in SKI, 2000c) that might affect the water flow beneath the ice and the occurrence of permafrost.

3.3.3 Hydraulic Evolution

The climate scenario provides a largely qualitative illustration of how different climate regimes affect the hydraulic conditions at the three repository sites. However, certain quantitative analyses have been conducted, to illustrate how the groundwater flow is affected when a continental ice front is at Aberg. SKB points out that the groundwater flows for the three sites are probably less than or comparable to present-day flows during the largest part of the next glacial cycle. Shorter periods with considerably higher flows occur once a melting zone or ice divide zone is at the sites. During these periods, the capability of the rock to limit the dispersion of radionuclides is reduced. However, the consequence analysis shows that any radiological consequences are negligible due to the considerable turnover of water and dilution in the biosphere.

In the opinion of the IRT (SKI, 2000a), the impact of the climate on the hydraulic and geochemical evolution must be studied in greater detail. Furthermore, the safety assessment would gain from more quantitative analyses, especially with respect to the conditions that could lead to oxygenated conditions at repository depth. SKI's consultant, Voss (SKI, 2000c) states that the hydraulic modelling is only performed on a local scale and only for one of the sites (Aberg). In Voss's view, other situations besides the location of an ice front directly above the repository must be analyzed. Voss mentions the risks of deep groundwater with high salinity flowing upwards. Furthermore, in Voss's view, it is a deficiency that SKB does not discuss combinations of unfavourable, but not completely improbable conditions such as high groundwater flow, buffer erosion, changes in groundwater chemistry and the formation of new water-bearing fractures.

In the authorities' opinion, as stated above, it is necessary to evaluate alternative climate predictions to obtain a more complete picture of the possible impact of the climate on the hydraulic conditions. The authorities also agree with the IRT that SKB should examine the importance of potentially unfavourable processes and conditions with quantitative analyses. For example, accumulation and subsequent flushing of radionuclides in connection with changed flow conditions is one interesting case. To assess the importance of this case, the entire climate sequence must be modelled, taking into account the dynamic changes in the groundwater flow and flow pattern. Another example is the importance of the mechanical impact of the continental ice sheet on the fractures in the rock and the groundwater flow pattern. Even if present-day knowledge of these coupled processes is deficient, sensitivity analyses can be used to identify critical issues.

3.3.4 Mechanical Evolution

The repository is subjected to mechanical influences during a glacial/interglacial cycle. This affects parameters such as the stress situation in the rock which, in turn, is coupled to a highly complex load situation that varies with time. SKB describes how a future ice cover can affect the groundwater and refers to calculation results that show that the rock movements that occur do not cause canister damage. The canisters are also expected to withstand hydrostatic pressure, but SKB points out that the canister calculations must be refined. The authorities share this opinion, especially in view of the fact that the canister is such a vital barrier in SKB's concept.

The groundwater flow will change when fractures are compressed or expand. The interaction between the mechanical load and the high groundwater pressure can lead to fracture expansion, known as hydraulic fracturing as well as closure, affecting the groundwater flow. In this way, there is direct feedback to the hydraulic evolution. In the authorities' view, SKB needs to show how it intends to deal with the interaction between processes (such as hydromechanical couplings) that can cause a greater impact than if the individual processes are analyzed separately. Stephansson (SKI, 2000c) would also like to see more information that can confirm the processes that occur in the rock in connection with glaciation, such as hydraulic fracturing and its impact on the groundwater flow.

The section dealing with the mechanical evolution in the geosphere at Aberg, Beberg and Ceberg is entirely based on the climate evolution described in SR 97 over the next 150,000 years. In future analyses, SKB should include the site-specific information that will be obtained from the forthcoming site investigations. This will allow for a better description of the conditions that exist at a site and by including it, it will also improve the basis for calculating the radionuclide transport.

SKB states that the strain energy that is stored in the bedrock can be released in connection with a deglaciation. Increased seismic activity and large earthquakes can therefore be expected during ice retreats. Therefore, in the authorities' opinion, the relationship between the ice load and movements in the bedrock should have been analyzed in greater detail and in a more integrated manner.

3.3.5 Chemical Evolution

The long-term evolution of the groundwater chemistry is of importance especially for the changes in the properties of the bentonite buffer as well as for radionuclide transport and possibly for canister corrosion. In the climate scenario, SKB describes possible evolution trends in Aberg, Beberg and Ceberg. SKB shows that the salinity can increase as well as decrease as a result of a passing ice front. Highly diluted glacial meltwater will penetrate into the rock and can displace existing groundwater at repository depth. Highly saline groundwater can also displace existing groundwater when it is transported upwards from greater depths. SKB states that the bentonite buffer should be able to withstand the chemical changes that can occur. SKB estimates that the margins for buffer erosion and colloid formation not occurring are low since there will be a large quantity of diluted water.

The pressure conditions in the buffer will change as a continental ice sheet passes over the repository. This affects both groundwater and hydrogen gas transport into and out of a defective canister. Hydrogen gas is assumed to form during the corrosion of the iron insert. SKB states that the pressure inside the defective canister is adapted to the surrounding pressure so that the isolating capability of the gas phase in the canister is maintained (see also Section 2.3.5 of this appendix).

The authorities consider that SKB's report provides a good overview of different phenomena that can affect the protective capabilities of the repository. However, there are a number of questions coupled to the stability of the buffer and possible changes that are only mentioned in SR 97 without any analyses or quantitative results being reported. Examples include SKB's evaluation of buffer erosion and colloid formation. To describe the importance of such phenomena, SKB would probably have to develop a more detailed model of the long-term evolution of the groundwater chemistry. An appropriate time to do this would be when an adequate quantity of geochemical data have been collected for a specific candidate site.

In the authorities' opinion, it still remains to be demonstrated that the gas pressure inside a canister with a corroding iron insert would adapt to the changes in the surrounding pressure induced by the glaciation, without affecting the buffer and canister. This case is not mentioned in the model studies that are the basis of SKB's canister model (see also Section 2.3.5 of this appendix). A possible impact on the engineered barriers, caused by the transient phases, cannot be excluded, such as movements in the bentonite material, gas transport etc.

In SR 97, SKB discusses different processes that affect the redox conditions at repository depth but has not analyzed in greater detail what happens if oxygenated glacial meltwater reaches repository depth. Instead SKB limits itself to stating that this case will probably not occur. This has been questioned by the IRT and by SKI's consultants, Arthur and Zhou, Glynn, Grambow and Voss (SKI, 2000c). SKB's REX project has shown that microbial decomposition of organic material is a dominant mechanism for oxygen consumption under present-day conditions (Banwart et al., 1996). However, for the ice age scenario, it has been assumed in several analyses that dissolved oxygen is consumed mainly through the weathering of silicate mineral containing Fe(II) (such as Arthur, 1996; Glynn and Voss, 1999; Guimera et al., 1999). In the authorities' opinion, the bedrock definitely has a considerable capacity to consume oxygen relative to the quantities that would occur. However, since Fe(II) is mainly bound to minerals that do not easily weather, slow kinetics can be a limiting factor, as shown in laboratory studies. In other contexts, it has been demonstrated that silicate weathering on the field scale is a very slow process, mainly due to the limited contact surfaces between the mineral and the mobile groundwater.

In the authorities' opinion, in general, Swedish bedrock should have a good capability to maintain reducing chemical conditions at repository depth. However the issue cannot simply be dismissed on these grounds since reducing chemical conditions – particularly on the canister surface and also to a certain extent inside the canister and inside the buffer – must be considered to be the cornerstones of the KBS-3 system's basic safety philosophy. In the authorities' view, a limited occurrence of oxygen in time and space at repository depth is less probable but cannot be excluded through the model studies, laboratory experiments or geochemical investigations that have so far been presented. Therefore, SKB should more clearly show how it has handled this issue in SR 97 and also show how a KBS-3 repository with intact and defective canisters could be affected. This issue should be investigated in future safety assessments and in connection with site investigations.

3.3.6 Biosphere and Climate Changes

SKB describes the protective capability of the repository after climate changes in a long-term perspective, which is required by the regulations of both authorities. Moreover, SSI's regulations (see Section 2.2.6) require that the protective capability should be described in specific detail for a shorter time-frame. SKB should deal with this issue in future safety assessments.

A climate change in a 1,000-year time-frame primarily concerns the biosphere. It is important to describe the impact that climate changes can have on exposure pathways, for example. Therefore, the authorities consider that SKB should, also in the climate scenario, describe the 1,000-year time period in view of the requirements of SSI's regulations. An important factor in this short time-frame is, for example, the greenhouse effect which causes global warming. In the authorities' opinion, in future assessments of the 1,000-year time period, SKB must describe the possible impact of the climate on the factors that are important in the assessment of a repository's safe performance.

3.3.7 Radionuclide Transport Calculations

SKB has prepared a description of a possible climate evolution for the three repository sites. However, SKB has decided to use a highly simplified assumption in its radionuclide transport calculations which means that the ice front is always directly above the repository. This assumption implies a continual outflow of radionuclides. In the authorities' opinion, SKB should have presented a clearer justification of why this simplified scenario has been chosen and why it can be considered to be conservative.

SKB states that radionuclide accumulation in the rock matrix and the impact of changes in the groundwater composition on sorption are of minor importance for the calculation results. In the authorities' opinion, SKB should have also justified these judgements more clearly, namely by providing illustrative calculations. Furthermore, it is not obvious to the authorities why only the calculations for Aberg have been explicitly reported while the results for Beberg and Ceberg are only provided as part of the reasoning in the discussion.

SKB states that dilution in the biosphere is an important factor for the calculated doses in the climate scenario. In view of the considerable uncertainty of predictions of future biosphere conditions and of SKB's decision not to assign a safety function to the biosphere, the authorities conclude that SKB should have specified the extent to which the biosphere has contributed to reducing the doses in SR 97 in relation to the geosphere.

In the authorities' view, the radionuclide transport calculations in SR 97 have been oversimplified, taking in to account the complexity of recurrent glacial, permafrost and temperate/boreal conditions. If the future climate evolution is not simply a repetition of the previous one, the scenario for Aberg could entail, for example, that the repository is below instead of above seawater for long periods of time. This could have had considerable importance for the consequence analysis. In the authorities' opinion, there is a need to take into account climate evolution alternatives in future assessments and to discuss the impact these could have on radionuclide transport.

4 Tectonics – Earthquake Scenario

4.1 SKB's Report

In the analysis of the tectonics/earthquake scenario, it is assumed that present-day climate conditions prevail in the future and the impact of future ice ages is not studied. SKB analyzes the probability of occurrence of an earthquake that can lead to canister damage. To do this, SKB uses available fracture data in order to develop fracture network models for the three repository sites – Aberg, Beberg and Ceberg. Canister-intersecting fractures are generated using these models. For each site, earthquakes are randomly distributed among zones situated within a distance of 100 km from the repository site. The effects of the earthquake on the canister-intersecting fractures are simulated by another code (POLY3D) which provides probabilities for canister damage. The evaluation of the calculations is based on the assumption that a shear movement of 0.1 m or more will result in canister damage. SKB states that this assumption must be tested by new calculations for the current canister design.

The results of the analysis show that there is a negligible risk of canister damage. However, SKB emphasizes that the analysis methodology is under development and is only an initial step in the quantitative analysis of earthquake scenarios.

4.2 Comments by the Reviewing Bodies

In the opinion of the Geological Survey of Sweden (SGU), it is highly probably that within a hundred thousand-year period, there will be one glaciation scenario which will have an impact on the fracture system and groundwater conditions in the rock. Extensive late glacial and post-glacial fault movements with subsequent strong earthquakes have been assumed to take place in the northern regions of Sweden. Everything points to a causal relationship between these fault movements and the deglaciation but further research is needed to analyse the importance of these phenomena. In SGU's view, these issues are important for the future safety of a repository.

Mörner, Stockholm University, questions SKB's method of using existing earthquake statistics in its analysis of earthquake risks throughout the lifetime of a repository, including future glaciations. Mörner is highly critical of the fact that SKB does not include existing knowledge of major earthquakes in connection with the deglaciation, since Sweden, according to Mörner, was a region with high seismic activity. Mörner points out that the earthquake frequency and the earthquake mechanisms were different than they are today. According to Mörner, this thereby excludes the possibility of the "extrapolation of existing statistics". Mörner also questions the statement that new rock movements in most cases follow already existing fracture zones.

SGU comments upon the assumption made in SR 97 that (mechanical) canister damage can be avoided by not siting the repository closer than 100 m from existing 100 km-long fracture zones which are presumptive future fault zones. SGU states that it has not been proven that the young rock movements have followed older planes of weakness in every case and definitely not the major zones. Instead, the rock movements seem to use several existing zones that are conveniently located in relation to the load or existing stresses.

In SGU's opinion, the relationship of the post-glacial fault to older planes of weakness must be better investigated in order to avoid siting a repository near to presumptive future zones of movement and in order to better understand the mechanisms behind the fault movements that occurred in connection with the last deglaciation. SGU also maintains that it is important to understand how fault movements affect the groundwater situation.

The National Council for Nuclear Waste (KASAM) points out the need to also take into account the effect of land uplift on the rock and its impact on water chemistry. Whether or not the effects of accumulated creep movements triggered in a particular part of the repository can result in damage to a significant number of canisters is an issue that must be investigated. According to KASAM, several investigations in Norway have shown a clear relationship between the land uplift intensity and the fracture conductivity and well conductivity.

4.3 SKI and SSI's Review and Evaluation

4.3.1 Premises for the Scenario

In the opinion of the International Review Team (IRT) (SKI, 2000a), the scenario is innovative and useful. However, the IRT is surprised that it is accorded such importance in SR 97, taking into account the fact that Swedish bedrock is considered to be stable.

The major (on the order of magnitude of 7 and above) earthquakes in Sweden are closely connected to climate-related effects (such as the deglaciation phase). The authorities questions how relevant it is to have a scenario dedicated to tectonics/earthquakes that is based on the base scenario including the assumption that present-day climate will prevail in the future. Climate-related issues such as deglaciation, in particular, can be of considerable importance for whether or not major earthquakes will occur.

The authorities are sceptical as to whether SKB can use existing earthquake statistics (from measurements conducted over a period of about 100 years) and extrapolate them one hundred thousand years in the future. This approach is also questioned by Mörner (SKI, 2000b). However, in the authorities' opinion, in its analysis, SKB covers the time period up to the next ice age.

4.3.2 Origin and Frequency of Earthquakes

SKB's report provides a good overview of earthquake mechanisms and how they are distributed in time and space.

The probability calculations that SKB presents for canister damage (caused by earthquakes with a magnitude greater than 5 on the Richter scale), are based on the extrapolation of existing earthquake statistics for Sweden and are assumed to apply one hundred thousand years in the future. The authorities consider the existing Swedish earthquake statistics to be of limited value, since the earthquakes have different origins, for example with respect to method of formation.

Extrapolations in time and space are always associated with major or minor errors and SKB points out accordingly that this stage in the analysis probably carries the greatest uncertainty. Whether or not the extrapolation applies to earthquakes formed through movements in the lithospheric plate or strains from the last ice age is currently an open question. SR 97 does not provide any clear answer to this question. In the authorities' opinion, SKB needs to explicitly describe the time-frame to which the results of the probability calculations apply. Therefore, the authorities do not consider that the calculations performed in SR 97 provide a good view of the risks for the time during and after a glaciation.

As is clear from SKI consultant, Stephansson's statement of opinion (SKI, 2000c), measurements from NORSAR should improve the database for the earthquake statistics. These measurements also cover seismic risk analyses for oil platforms. This could be of assistance in analyzing the probability of movements that can affect a repository.

In the authorities' opinion, future geodetic measurements, based on satellite data, should provide a more unambiguous and systematic picture of the horizontal strains now occurring in the Baltic Shield. They should also improve the understanding of why certain regions have greater seismic activity than others. This is also proposed by SKB discussing possible future improvements in the earthquake probability analysis.

4.3.3 Mechanical Impact on the Rock

SKB maintains that there is a consensus that fault movements along post-glacial faults probably occurred as a result of the reactivation of existing fractures rather than through new fracture formation. However, some researchers hold a different opinion on this view and the database is limited. Therefore, in the authorities' opinion. SKB should elucidate more fully the importance of fault movements caused by reactivation and new formation, for example, with the help of sensitivity analysis.

In the view of the IRT (SKI, 2000a), the tectonics/earthquake scenario lacks an analysis of transient hydraulic effects (seismic pumping) and possible implications of these effects in a long-term perspective (for example the impact on groundwater chemistry). SGU (SKI, 2000b) and Glyn and Geier (SKI, 2000c) raise the issue of deficiencies in the handling of coupled effects, such as movements along fault zones that affect the groundwater flow (see also Appendix 2, Chapter 3). Issues relating to these and similar secondary effects should be investigated in greater detail in future safety assessments.

SKB states that fracture zones of a certain size should be avoided in order to minimize the probability of canister damage (according to SKB's probability estimate).

Stephansson and Geier (SKI, 2000c) both point out the need for a more stringent and exhaustive definition of what SKB means by "respect distance" and the contexts in which SKB will use this term. Tirén (SKI, 2000c) raises the problem of the characterization of fracture zones, such as how they can be delimited. SGU (SKI, 2000b) also states that it is not obvious that it is possible to detect all fracture zones and presumptive future zones of movement that can result in (mechanical) canister damage in connection with future earthquakes near to the repository. The authorities assume that SKB's future report on site investigations will contain a description of how SKB intends to handle the issues mentioned above.

4.3.4 Importance for the Safety Assessment

SKB's calculations show that the probability of canister damage caused by earthquakes is on the same order of magnitude as that assumed for initial canister damage. SKB further states that the probability of canister damage is negligible in practice and refers to the fact that pessimistic assumptions have been made in the calculation model (the importance of friction for rock movements has been neglected) and that major fracture zones can be avoided in connection with canister emplacement. Consequently, in SKB's opinion, it is not necessary to perform radionuclide transport calculations in the tectonics/earthquake scenario.

The authorities do not consider that the comparison between the damage frequency as a result of rock movements and the probability of initial canister damage is useful since a shear movement could damage all of the engineered barriers. In the authorities' opinion, SKB's conclusions on the importance of the earthquakes for repository siting, are difficult to evaluate and recommends that SKB should evaluate the effects of shear movements on all barriers in future safety assessments.

SKB sees a need to develop methods to estimate the probabilities of earthquakes and, in SKB's view, the report in SR 97 is only an initial step towards developing an approach for the quantitative analysis of earthquake scenarios. Thus, the authorities conclude that SKB is highly conscious of the fact that the knowledge base is limited. However, the authorities question the method of separating mechanisms that are basically coupled (cause-effect) as is the case in the strategy for handling earthquakes in SR 97. One alternative would be to treat a large number of mechanisms such as earthquakes and climate changes (ice loading - unloading) in a single scenario and in an integrated manner.

5 Scenarios Based on Human Actions

5.1 SKB's Report

SKB has put considerable effort into discussing the premises for human actions that would have an impact on the repository and subsequent radiological consequences. SKB has analyzed cases that lead to intrusion into the repository, such as in the form of deep drilling through the repository. The important social and technical conditions that would result in unintentional intrusion are evaluated. Various scenarios for societal evolution and societal knowledge of the repository have been studied through expert judgements (in the form of morphological field analysis) and through a discussion of these evaluation tools.

5.2 Comments by the Reviewing Bodies

Only the International Review Team (IRT) (SKI, 2000a) has expressed an opinion on SKB's description of intrusion and scenarios leading to intrusion. In the opinion of the IRT, the analysis is well thought-out and has been developed by SKB to a level corresponding to that of other national programmes that have dealt with this issue. A valuable component is that the analysis can be a starting point for continued dialogue with the authorities regarding what is required with respect to this issue.

5.3 SKI and SSI's Review and Evaluation

5.3.1 Philosophy

International studies on intrusion have, as a rule, been based on the principle that society must assume responsibility for its own conscious actions. No-one today can adopt credible measures to prevent a deliberate intrusion into a waste repository in the future. Therefore, the discussion of these studies primarily focus on unintentional intrustion (NEA, 1995b).

Various strategies concerning what must be reported and evaluated have been introduced with respect to the effects of human action on the whole, including actions on a global and regional nature. One strategy could be to do as SKB has done, namely to present lines of argument concerning the evolution of society and to use this analysis as a basis of discussing the probability of various scenarios. Another strategy could be to adhere strictly to present-day human activities in scenario formulation. The justification for the latter strategy would be to avoid too much speculation about the future evolution. In the authorities' opinion, it could be valuable to include both of these approaches to obtain a complete basis of evaluation. In the authorities' view, the analysis of certain scenarios, especially those involving intrusion into a repository, should primarily be used in the evaluation of a strategy and method for the management of nuclear waste. Many of these issues have been discussed in a recently published status report (Wilmot et al., 1999).

Another distinction that is often made in studies concerning intrusion is the boundary between dose and health effects to the group causing the intrusion and doses to members of the general public who are not involved in the actual intrusion, but who are affected by an outflow from the repository caused by the intrusion.

SSI has not established any dose limits for events resulting from an unintentional intrusion. However, it is a regulatory requirement that this issue should be studied to provide a comprehensive picture to the authorities and other decision-makers of the risks associated with the repository. Above all, it is the repository's capability of retaining the radioactive substances after an intrusion that must be described.

According to the authorities, the analyses that SKB has conducted concerning the possible evolution of society and its importance for intrusion may be of benefit in the evaluation of passive systems, archives etc. that may be established at a subsequent stage.

Although the authorities have not made any requirements in their regulations regarding the scenarios reported by SKB and the underlying argumentation, the authorities share the IRT's opinion that SKB's work in this area is valuable. SKB's work can provide some basis for further dialogue with the authorities concerning what must be presented in the more detailed material that the authorities will require in later versions of the safety assessment.

5.3.2 Protective Capability of the Repository after Intrusion

Both SSI's (SSI, 1999) and SKI's regulations on final disposal require that the protective capability and performance of the repository after intrusion should be described. The regulations do not regulate the calculations in detail since intrusion can take many forms. SKB has made assumptions concerning boreholes and bentonite properties in connection with intrusion, and reports doses to members of the public after intrusion in Section 12.6.3 "Radiation Dose and Risk to the Family". However, in the opinion of the authorities, SKB has not presented any data to support the claim that the buffer and backfill will perform as intended after such damage.

SKB's analysis is evaluated as satisfactory, based on the premises that apply at the present time.