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A summary of biospheric research 1975–1997

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Abstract

The aim of this study is to present a summary of the work performed within the frame of SKB's biosphere programme during 1975 – 1997. The studies focused on field studies and theoretical model development. Important problems identified during this time period are pointed out.

Summaries of the biospheric parts of the safety analyses performed since 1977 are given. Models are described as well as basic assumptions. Already the first analysis had an overall approach including dispersion from local to global zones with multiple exposure pathways. Compartment models have been used whereby the rate constants in the first assessments were mostly based on observed redistribution of radionuclides in nature. During the years emphasis has been laid on the description of processes mathematically and additional processes have been included in the models. In general, standard biospheres with constant environmental conditions were applied with focus on releases of radionuclides to wells, lakes and coastal areas. Drinking water has shown to be an important exposure pathway but not always the dominant one. Some screening calculations performed showed that peat bogs may be important recipients when doses to humans are concerned.

The field studies initially focused on the naturally existing isotopes of U and Ra. A lot of studies were performed to gain data concerning the levels of these radionuclides in soils and waters. The studies also obtained information about back-ground values and the distribution between various biospheric components which was used to support model assumptions.

A special sampling programme with the purpose to outline influence of drying up of lakes on the dose to individuals of critical group was also performed. The dose calculations showed that the doses could increase two orders of magnitude for immobile elements when the lake had dried up. Investigations of the natural abundance of radionuclides in soil and flora were performed later. After the Chernobyl accident the behaviour of Cs-137, as well as other isotopes, in the environment was studied. The results were used to further improve the biosphere modelling.

Other field studies were related to studies of groundwater entrances to lake sediment and the outflow of spring water under oxidising and reducing conditions. Intensive field work has been performed at the Äspö area whereby, among other things, long sediment cores have been sampled and analysed.

The modelling of physical/chemical processes have been improved and the flexibility of the models has increased. One important improvement is that the models now are able to include full decay chains. At present ten nuclides in a chain can be modelled.

The models have also been used in international model validation studies of which summaries are given in the report. One important conclusion from those studies was that it is important that field studies and model development are performed parallelly and

that the co-operation between experimentalists (field studies) and modellers is close when designing conceptual models.

A large number of technical reports and notes have been published during the years while scientific publications have been scarce.

Sammanfattning

Syftet med denna studie är att presentera en sammanfattning av det arbete som utförts inom ramen för SKB:s biosfärsforskningsprogram under åren 1975 – 1997. Studierna fokuserades på fältstudier samt teoretisk modellutveckling. Viktiga problem som identifierats under denna tid pekas ut.

Biosfärsdelarna i säkerhetsanalyserna gjorda sedan 1977 sammanfattas. Modellerna är beskrivna liksom grundläggande antaganden. Redan den första säkerhetsanalysen hade ett övergripande koncept som inkluderade spridning från lokala till globala zoner med många exponeringsvägar. Kompartmentmodeller har använts där överföringsfaktorerna i den första säkerhetsanalysen främst baserades på observerad omfördelning av radionuklider i naturen. Under åren har tyngdpunkten legat på beskrivandet av processer matematiskt och fler processer har inkluderats i modellerna. Generellt användes standardbiosfärer med konstanta biosfärsförhållanden och fokus låg på utsläpp av radionuklider till brunnar, sjöar och kustområden. Dricksvatten visade sig vara en viktig exponeringsväg men inte alltid den dominerande. Några undersökningsberäkningar visade att torvmossar kan vara viktiga recipienter när det gäller beaktandet av doser till människa.

Fältstudierna fokuserades initialt på naturligt förekommande isotoper av U och Ra. En hel del studier genomfördes för att erhålla data rörande nivåer av dessa radionuklider i jordar och vatten. Studierna gav också information om bakgrundsnivåer och fördelningen mellan olika biosfärskomponenter vilket användes för att stödja modellantaganden.

Ett speciellt provtagningsprogram genomfördes med syfte att kartlägga hur upp-torkandet av sjöar påverkar dos till kritisk grupp. Beräkningarna visade att dosen från orörliga element kunde öka upp till 2 storleksordningar när sjön hade växt igen. Senare genomfördes undersökningar av naturligt förekommande radionuklider i jord och flora. Efter Tjernobylolyckan studerades beteendet av Cs-137 och andra radionuklider in miljön. Resultaten användes för att ytterligare förbättra biosfärsmodelleringen.

Andra fältstudier var relaterade till studiet av grundvattenutflöde i sjösediment liksom utflödet av källvatten under oxiderande och reducerande förhållanden. Fältstudierna vid Äspöområdet har varit intensiva där bl a långa sedimentkärnor tagits upp och analyserats.

Modelleringen av fysikalisk/kemiska processer har förbättrats och modellernas flexibilitet har ökat. En viktig förbättring är att modellerna nu kan hantera fullständiga sönderfallskedjor. För tillfället kan tio nuklider i en kedja modelleras.

Modellerna har också använts i internationella valideringsstudier vilka summeras i rapporten. En viktig slutsats från dessa studier var att det är viktigt att fältstudier och modellutveckling sker parallellt och att ett nära samarbete existerar mellan experimentalister (fältstudier) och modellerare.

Ett stort antal tekniska rapporter och skrivelser har publicerats under årens lopp medan de vetenskapliga publiceringarna varit få.

Table of contents

1 Introduction

This report attempts to summarise the biospheric parts of safety analyses for repositories for radioactive waste in Sweden as well as biospheric research performed at the request of SKB during more than 20 years. It also includes a definition of the biosphere and briefly describes biospheric modelling. Safety analyses performed for deep bedrock repositories for spent fuel, and for low-level and intermediate level waste, are summarised with regard to biospheric modelling in Chapter 2 and Chapter 3, respectively. A tool for calculation of doses to humans due to release of radionuclides into the biosphere is described in Chapter 4. Several investigations to obtain data by e.g. field studies are summarised in Chapter 5. A history of code development and evaluation of models is given in Chapter 6, whereas effects on biota other than humans are treated in Chapter 7. A description of computer codes used in the biospheric safety analyses is finally given in Chapter 8.

All abbreviations for facilities, projects and institutions, referred to in this report, are listed in Appendix A.

1.1 Background

In April 1977 the Stipulation Act was passed by the Swedish Parliament. The Act set forth requirements for the demonstration of a safe management of spent nuclear fuel before any new reactors were permitted to be taken into operation. As a consequence, two safety analyses [KBS-1, 1977 and KBS-2, 1978] were performed. The first was concerned with final disposal of high level vitrified reprocessing waste. The plans to reprocess spent nuclear fuel were later abandoned, the consequence of which was that KBS-2 treated disposal of non-reprocessed spent nuclear fuel. After that four reactors were given permission to start. These two safety analyses were followed by a further safety analysis for disposal of spent nuclear fuel, [KBS-3, 1983], considering new aspects and data due to research and development. The two last of the 12 reactors in the Swedish nuclear programme were after that taken into operation. Since then, a study of an alternative method for storing spent nuclear fuel, WP-cave, (see Section 2.4) and SKB-91 [SKB, 1992] (see Chapter 4) were performed. Furthermore, a safety analysis for the Final Repository for Radioactive Operational Waste (SFR) was issued in 1987 [SSR, 1987]. Beside these safety studies, several field investigations and literature surveys were carried out in order to gather relevant data regarding biospheric processes. A continuous model development has also been performed.

The system for management of nuclear waste in Sweden is at present as follows (see Figure 1-1). Spent fuel is after discharge kept at the nuclear plant for about one year, after which it is transferred to the Central Interim Storage Facility for Spent Nuclear Fuel ("Centralt mellanlager för använt bränsle," CLAB) in Oskarshamn. After at least 30 years of storage the fuel is planned to be positioned within a deep geological repository in bedrock at about 500 m depth. The location of such a repository is not yet decided. The objective of the system for long-term storage is to isolate the spent fuel from the biosphere at least until the level of radioactivity has been reduced to that of natural uranium ore. This will take some 100 000 years. The isolation is achieved by using multiple technical and natural barriers. The spent fuel dissolves very slowly in water. The zircalloy tubes in which the fuel pellets are kept contribute to the isolation. The fuel rods are kept in canisters consisting of an iron matrix, providing mechanical stability, and a copper casing, which protects against corrosion. The canisters will be surrounded by bentonite, which protects against small movements of the surrounding rock and in the event of leakage slows the dispersion of radionuclides. This is an effect also caused by the bedrock itself, because the location of the repository will be selected so that there will not be any rapid turnover of groundwater. The net transport velocity for radionuclides is then less than that of the transporting water, due to sorption in small fissures, thus contributing to the retardation of nuclides. Should all of these barriers fail, radionuclides could eventually reach the biosphere, and possible harm to human might ensue. How such a failure could happen, as well as dispersion in the biosphere and resulting doses are treated in safety analyses [SKB, 1999].

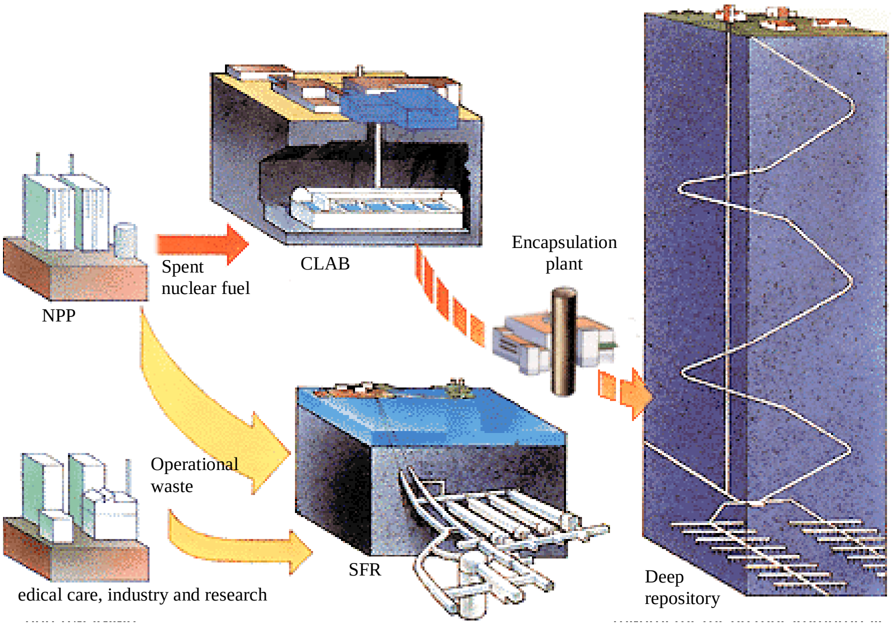


Figure 1-1 *The Swedish system for management of nuclear waste. The encapsulation plant and the deep repository are under planning.*

1.2 The biosphere

The term ”biosphere” includes all living organisms, and in a broad sense their surrounding environment as well. The biosphere thus includes media in the environment which sustain living organisms, i.e. the entire hydrosphere and parts of the atmosphere as well as the upper lithosphere. The position of the biosphere when calculating consequences from failures of barriers is shown in Figure 1-2.

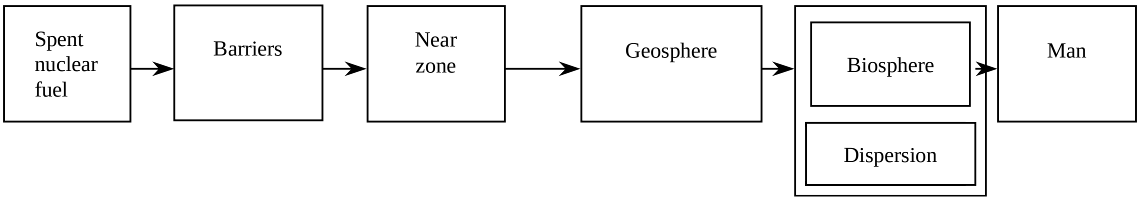


Figure 1-2 *The position of the biosphere when calculating doses to the most exposed individual from unpostulated leakages of radionuclides from a repository for spent fuel.*

1.3 Biospheric modelling

Biosphere model calculations of doses to humans due to calculated leakage of radionuclides from the geosphere (bedrock and deep groundwater) are included as a part of the safety analyses mentioned above. Due to this, biosphere research within different areas was initiated for improvements of the safety analyses. Topics that have been studied within the biosphere research by SKB and also by corresponding organisations in other countries are shown in Figure 1-3. As illustrated, underlying research and development, model improvement and safety analyses are interactive processes closely related to one another. The technical design of the repository and the location are fundamental for a biospheric safety analysis. They constitute the basis for release scenarios, in which the technical design determines the source term into the biosphere (via processes in the geosphere), and the location sets the biospheric conditions. It has been the case, however, that safety analyses had to be performed with generic data, because no specific location was given. Biospheric models (conceptual and numerical) are developed based on the scenarios.

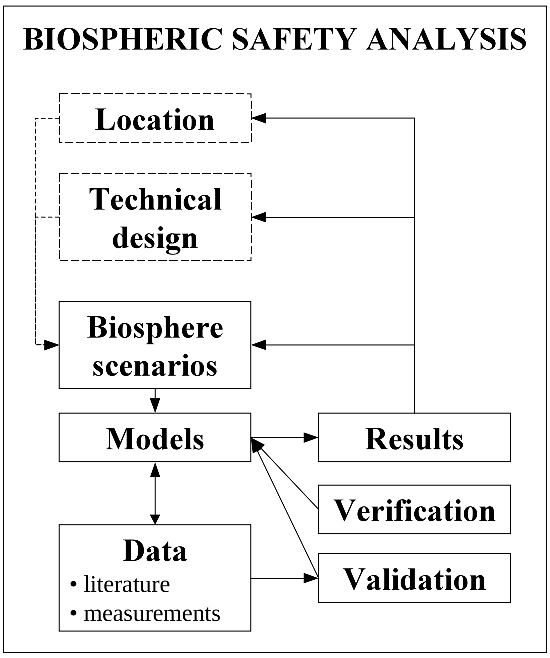


Figure 1-3 *Illustration of the major steps in the process of model development for illustrations of doses in a safety analysis.*

Verification and validation are very important in order to gain confidence in model results. Verification is to check that models yield results according to the specifications. The validation process is to compare model results with independent measurements from the biosphere. In the case of long-term repositories, it is of course impossible to measure turnover of substances in the biosphere for several hundred thousand years. Validation of model processes must therefore be performed for biospheric conditions as they are today, and for sub-processes during shorter time periods.

Both measurement data and model parameter data may be found from literature. When developing models, however, requirements for new or improved data often ensue, and measurements must then be performed. The model results could have an influence on the technical design, and the location, but also on the creation of new scenarios, e.g. when choosing areas for refinement of the models.

Technical design and location have not been considered in this report, but all of the other aspects of Figure 1-3 are treated.

The evaluation of a safety analysis for design of a deep bedrock repository is among other things based on an analysis of the extent to which individuals and population may be exposed due to potential leakage of radionuclides from a repository. The analysis takes into account the long-term turnover of different radioactive elements in the biosphere, and estimates radiation doses to human. From now on doses to biota must also be estimated (SSI, 1998). Since the forecasts must be projected over very long spans of time, due to the presence of long-lived radionuclides in the spent fuel, uncertainties of various kinds are introduced. For example, the biosphere in 100 000 years, after one or more ice ages, might be significantly different than that of today. The approach has been to use current conditions, according to regulations from SSI [1998]. The long time spans made several rather complex processes possible to model using averaged values, e.g. there was no need to consider seasonal variations. Compartment models were used, and time steps in the order of years and longer, with the simplifying assumption of complete mixing of radionuclides within the compartments during each time step.

From the middle of the 80's, the ambition has been to take uncertainties into account by analysing the variations around mean values of the parameters, e.g. uptake in plants or in fish. Earlier when this has not been applicable, the description has been based on assumptions and choices of values that probably do not underestimate the radiation doses to man.

2 Safety analyses for deep bedrock repositories for high level waste

2.1 KBS-1 (1977)

KBS-1 was the first safety analysis for final disposal of vitrified reprocessed high level waste [KBS-1, 1977]. The base case was that the canisters would degrade slowly, starting 1 000 years after closure of the repository. An initial canister failure was also considered, as well as varying times for degradation of the glass.

The computer code BIOPATH (see Section 8.1) was developed and applied for calculations of doses to critical groups, integrated over 30 years, and global population due to turnover of radioactive nuclides entering the biosphere by groundwater transport [Bergman et al., 1977]. The hypothetical "critical group" was assumed to consist of individuals with habits that would give them a high dose, e.g. people living in "contaminated" areas of the countryside and being nearly self-sufficient in food production.

2.1.1 Biosphere scenario and model

Three main inflows of radionuclides into the biosphere were considered. They were all based on a groundwater-borne transport of radionuclides from a deep repository (see Figure 2-1):

- Inflow to a well located in a valley (well scenario)
- Inflow to a fresh water lake, Finnsjön, (lake scenario)
- Inflow to the Baltic Sea (coast scenario).

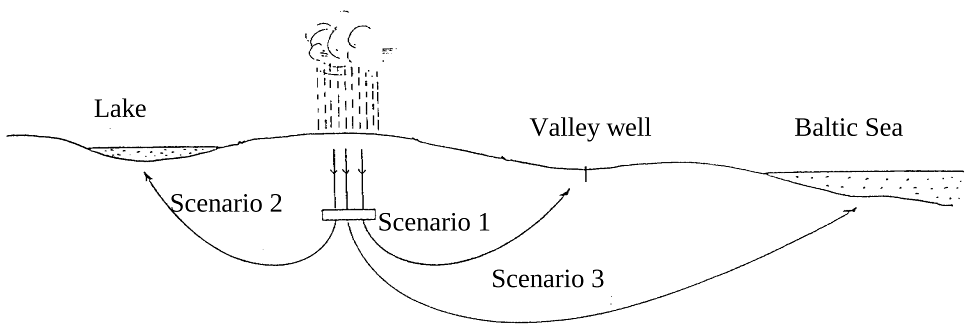


Figure 2-1 *Illustration of the three main scenarios for transport of radionuclides to the biosphere used in the KBS-1 study.*

The ecosystem was divided into a number of physically well-defined areas or volumes (compartments). Constant reservoir sizes over time were assumed in the model calculations. In all, 13 exposure pathways were included of which nine were due to consumption of various types of foodstuffs and water while the remaining four were external exposure from radionuclides in soil, water and sediment. The model included four interconnected regions, each one consisting of a number of compartments, within and between which nuclides were assumed to be transferred : the local area, the regional area, the intermediate area and the global area (see Figure 2-2). The model could at that time only treat a simple parent-to-daughter decay chain.

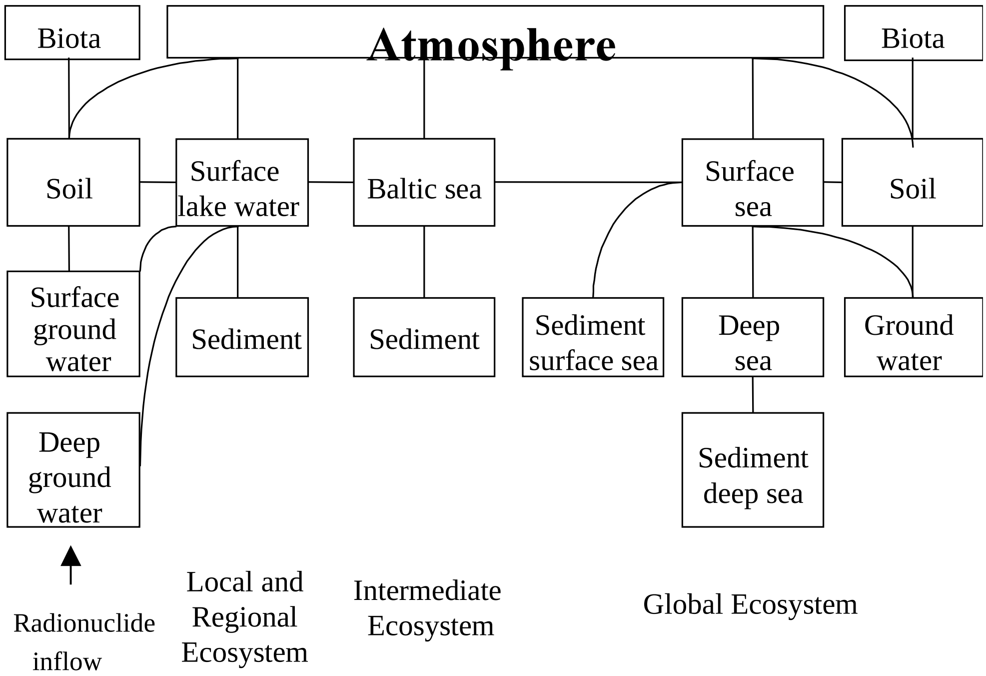


Figure 2-2 *The various reservoirs used in KBS-1 and 2 (KBS 1, 1977). when calculating the gradual dispersion of radionuclides from the local area out to the global area and resulting exposures. The details for the local ecosystem are not shown.*

Radionuclides were assumed to be carried with water and particulate matter. The turnover of radionuclides was therefore governed by the water turnover and diverse transfers:

- Water turnover
- Wet and dry deposition
- Irrigation and resuspension
- Transfer from water to sediment
- Transfer from sediment to water

- Transfer from groundwater to soil
- Transfer from groundwater to surface water
- Transfer from soil to groundwater

The elements were divided into groups with similar properties in order to obtain rate constants for the radionuclide transport. The rate constants were mostly based on results of nuclide distribution during varying time periods instead of considered various processes explicitly.

The internal exposure pathways were calculated by use of ”enrichment and distribution” factors, which were element specific. They correspond to what nowadays are called as bioaccumulation and root-uptake factors. The approach is based on the assumption that steady state conditions between biota and the biosphere component, e.g. water or soil, are prevailing, in similarity with present-day modelling of uptake in food chains [BIOMOVS II, 1996b, Davis et al., 1993 and Bergström et al., 1999].

2.1.2 Data

The calculations were performed for 16 radionuclides: These were Sr-90, Zr-93, Tc-99, I-129, Cs-135, Cs-137, Ra-226, Th-229, Th-230, U-233, U-234, Np-237, Pu-239, Pu-240, Am-241 and Am-243. Nowadays more than twice as many radionuclides are included in the safety assessments [Bergström et al., 1999].

Several information sources were used in order to obtain data for common as well as element specific rate constants. Data common for all nuclides were used for rate constants coupled to water-turnover, wet and dry depositions, and resuspension. Element specific rate constants were applied for:

- Transfer from water to sediment
- Transfer from sediment to water
- Transfer from groundwater to soil
- Transfer from groundwater to surface water
- Transfer from soil to groundwater

Data on redistribution of radionuclides found in the literature were divided with pertinent time periods in order to obtain annual rate constants. When no such information was available about e.g. migration in soil and groundwater of the elements a so-called distribution factor was used together with the water turnover times for obtaining the rate constants. The distribution factors were taken from data about Western US desert soil in lack of other information.

The water volumes used for mixing of the radionuclides in well and lake were 500 000 m^3 and 25 000 000 m^3 respectively. The volume for the well was obtained by assuming that the annual infiltration of precipitation over an area of 2 km^2 was available while data for the lake was taken from Lake Finnsjön.

2.1.3 Results

Results in this section pertain to the base case, i.e. slow degradation of the canisters. The results from dose calculations to the critical group showed that drinking water from a well was the dominant exposure pathway for the well scenario, the doses of which were the highest. The largest contributors to the dose were Np-237, Tc-99, U-233 and Ra-226.

The exposure via consumption of fish dominated in the lake and coast cases. External exposure was, however, the dominant pathway for Cs-135 and Th-229 in the coast case. The dominance of external exposure for these nuclides may be explained by the simplification to use the same radionuclide concentrations for beaches as for sediments. Cs-135 and Np-237 gave the largest contributions to the individual dose. Dose rates, time for maximum exposure and most significant exposure pathways (see Figure 2-3) were presented for three scenarios, both for unit releases of the radionuclides and for specified source terms. The collective dose commitments were dominated by I-129, Cs-135, Np-237, Th-229 and Tc-99.

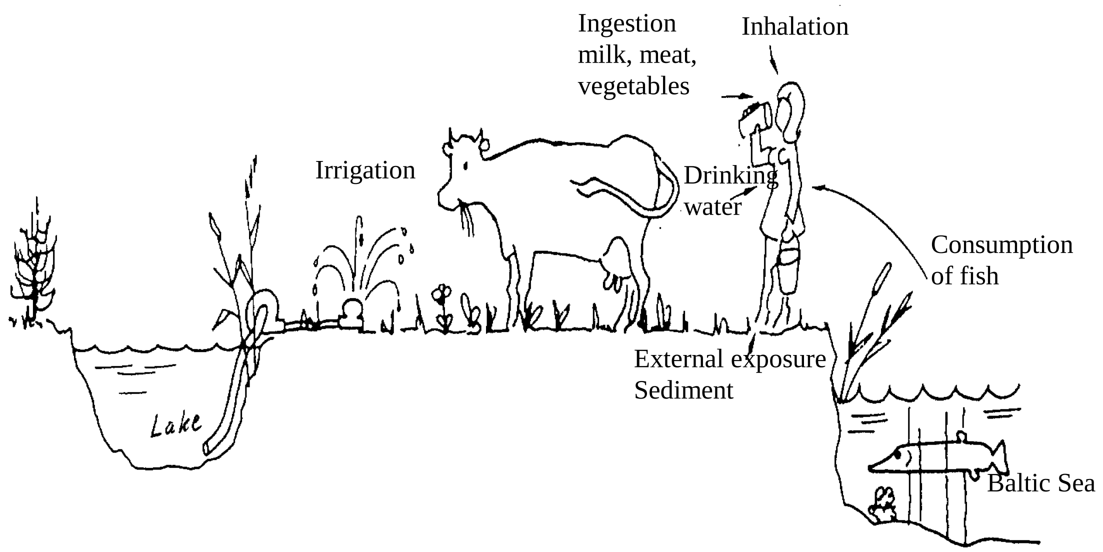


Figure 2-3 *Potential main exposure pathways to humans from radionuclides in water, soils, air and sediments.*

The simplification of ignoring the interface between the geosphere and the biosphere was not discussed in the report. However, variations in results due to variations in rate constants, exposure pathways, selection of values for enrichment factors and sizes of populations were discussed.

2.1.4 Conclusions

Main conclusions were:

- The maximum individual dose commitment during 30 years would not exceed 4 mSv. This is about the same as the maximum permitted dose from normal operation of Swedish nuclear power plants.
- Leakage from a few initially damaged canisters would not cause any significant doses.

2.2 KBS-2 (1978)

The next safety analysis, KBS-2, [KBS-2, 1978] was based on direct disposal of spent nuclear fuel, in contrast to KBS-1, which treated vitrified reprocessing waste. The model system design was basically the same as in KBS-1, see Section 2.1. More emphasis was however put on obtaining element specific rate constants for the radionuclides. In addition, the global cycles of iodine and carbon were considered. Furthermore, annual doses to critical groups and the global population were calculated for 22 radionuclides of relevance for directly disposed spent fuel. The presentation in Sections 2.2.1 – 2.2.5 is based on Bergman et al., [1979].

2.2.1 Scenarios

Doses were calculated for different source terms, based on several scenarios for canister damages and geosphere transport of radionuclides [KBS-2, 1978]. The main case was that the canisters will be penetrated after 100 000 years, and the dissolution of radionuclides will continue for 500 000 years. Two assumptions regarding water transit time and retention factors were made; the main case and one "pessimistic", which had a lower retention factor in the rock and hence a shorter transit time to the biosphere. For each of these cases, the primary biospheric recipients were postulated to be a well, a lake and the Baltic sea, respectively, thus yielding six scenarios.

2.2.2 Model design and exposure pathways

The 13 pathways of exposure taken into account were the same as in KBS-1 (see Section 2.1.1). Radioactive nuclides may be introduced into the food web via deposition on plants, uptake via root systems or uptake in aquatic biota . Those exposure pathways were considered, in addition to external exposure from radioactivity in the air, ground and water.

2.2.3 Data

As water was assumed to be the main carrier of the radionuclides most rate constants were obtained from hydrological information of the areas combined with element specific distribution coefficients, nowadays usually called K_d-values. The sizes of the annual volumes for mixing in the well and the lake volume were the same as the ones used in the previous KBS-1 study.

2.2.4 Results

One peculiarity in the results was the high contribution to doses to critical groups from consumption of water from so called secondary wells. Secondary wells were wells located in ground water underneath soils contaminated by lake water used for irrigation. The irrigation water was assumed to have migrated downwards in the soil and reached the well with the groundwater. The reason for the high contribution to dose was that the whole amount of radionuclides present in the aquifer was assumed to be in the water phase and thus contributing to the doses. This mistake was corrected later on in KBS-3 by considering a distribution coefficient describing the element concentration between water and solid material in the aquifer.

Maximum annual individual doses and annual collective dose commitments were presented. The main conclusions were:

- In the well case, drinking water comprises the dominant path of exposure for most nuclides. However, consumption of fish is the most important source for Cs-135 and consumption of meat is the most important source for C-14 and I129.
- In the lake case, fish consumption or drinking water is the most important path of exposure.
- In the Baltic coastal zone, the exposure is generally dominated by fish consumption. As regards Th-229, external exposure from fishing tackle and beach activities is responsible for most of the radiation dose.
- Different paths of exposure can dominate depending on whether the nuclide is carried out by groundwater from the repository or is generated via the decay of a long-lived parent nuclide that has already reached the biosphere, e.g. Ra-226 and Th-229.
- For a given nuclide, the maximum dose to the critical group and the maximum collective annual dose to the population are often obtained at different points of time. Moreover, the dose to the critical group is often heavily dependent upon the type of inflow.
- In the main case, the scenario with a well as primary recipient showed the highest maximum individual total dose rate: 0.11 mSv/year.
- In the “pessimistic” case, the scenario with a well as primary recipient showed the highest maximum individual total dose rate: 0.70 mSv/year. Dominant nuclides are Ra-226, Th-229, Np-237 and Pa-231.
- The collective doses vary to only a relatively small extent between the scenarios. The maximum annual collective dose for the main case was 0.17 manSv/year, due mainly to I-129. The corresponding value for the “pessimistic” case was about 1 manSv/year. The collective dose commitment for the worst 500-year period was 85 manSv.

2.2.5 Reliability of the model

The reliability of the calculated doses was dependent upon the structure of the model, variations in exchange between the reservoirs in the ecosystem, the choice of exposure pathways, approximations in the calculations and uncertainties in the utilised data.

Numerical approximations

Uncertainties originating from numerical approximation were found to be no more than 20 %, in most cases less than 5 %, of the dose values.

Variations in exchange between reservoirs and other parameters

Transfer coefficients for the exchange of radionuclides between the reservoirs in the model were calculated for each nuclide. These coefficients were derived from empirical and calculated literature data. In some cases, the data range was large. The dose calculations were based on conservative values, generally giving the highest dose to the critical group as well as to populations.

The degree to which uncertainties in the transfer rates between different reservoirs affected the result with regard to doses to critical groups and the different populations was investigated by variation of the values of the transfer parameters. Varying several other parameters for turnover of the radionuclides in the biosphere also lead to considerable changes of the results.

The doses for the well and lake alternatives for Cs-135, Ra-226 and the uranium isotopes were significantly influenced by such variations. This is exemplified below:

- The range in data for the exchange between soil and groundwater or between sediment and water was shown to lead to a variation of the dose with a factor of two for above-mentioned nuclides in the local or regional area.
- The concentration factors for fish varied depending on the type of ecosystem and on estimated uncertainties. In the case of Cs-135, the dose might vary by a factor of five in either direction. In the lake alternative, the doses showed differences by a factor of four for Ra-226 and a factor of two for the uranium isotopes.
- Variation of water turnover in the coastal zone in the Baltic Sea scenario lead to a variation of the dose by a factor of two.

Variations in consumption and population position and uptake through the food chains

A diet composition was established for the critical group. For Cs-135, Ra-226 and U-233, consumption of water, fish and milk were the most important pathways of exposure. A relatively high fish consumption rate, 50 kg per year and individual, was assumed. A reduction with 50 % lead to a dose reduction of 50 % for Cs-135 and less than 30 % for Ra-226 and U-233. Reasonable changes in the consumption of dairy products had a minor effect on the dose.

Changes in the distribution of the regional population and its food-intake habits can affect the calculated collective doses. This applies especially to the relatively short-lived or poorly soluble nuclides for which the collective dose primarily derives from the regional load. The assumed population density of 20 persons per km^2 represents the average for Sweden. An increase of the population, for example in a future high-density area, can lead to a limited increase of the collective doses depending on the critical pathways of exposure for the different nuclides.

The yield of fish from the lake was set to 60 000 kg/year, which is a certain overestime. Since fish consumption in general was shown to be the predominant path of exposure in the region, no increase of the regional collective load in the inland alternative was therefore to be expected, in view of the limited supply of fish from the primary lake recipient.

An increased population density can hardly lead to any increased collective doses for a region when foodstuffs such as milk and meat constitute critical pathways of exposure, since the increase in the population occurs at the expense of the cultivated acreage. When, on the other hand, drinking water constitutes the predominant pathway of exposure, the regional collective dose can be expected to be proportional to the number of people drinking contaminated water.

Daughter nuclides in decay chains

This section presents a refined analysis of decay chains, and transfer factors, which lead to lower calculated doses compared to those of KBS-1.

In decay chains with radioactive daughter nuclides, the distribution of the daughter nuclides among different parts of the biosphere partly depends on the turnover of their precursors. Uncertainties in the turnover of a precursor can, in some cases therefore affect the dose calculations for the daughter nuclide. In view of this and of its relatively high dose contribution, the decay chain U-234 - Th-230 - Ra-226 was determined to be of particular interest.

Thorium is slowly dispersed through soil relative to its physical decay rate ($t_{½}$ = 77 000 years). Variations in the exchange rate between soil and groundwater therefore have a relatively insignificant effect on the amount of thorium in the soil. With inflow of radioactivity into an inland area, the amount of Ra-226 to which the critical group and the regional population are exposed therefore primarily depends on how quickly uranium and radium are transported through the surface soil, since this has a considerable effect on the radium level both in the food chains and in the groundwater that can reach wells in the surrounding area.

Studies of the transport of uranium and its daughter products indicated that uranium was leached much faster through typical Swedish soils than was assumed in previous studies pertaining to vitrified waste. The field and laboratory studies [Allard et al., 1977 and Allard et al., 1978], which were carried out for strontium and radium, indicated that radium was dispersed much more slowly than strontium through soils and under very diverse conditions. In previous studies, however, radium was assumed to migrate at the same rate as strontium. These changes in the transfer rates in the soil-groundwater system for uranium and radium were found to lead to a reduction of the exposure of the critical group and the regional population that varied with the assumed type of inflow. In the main case discussed above, the doses from the intake of radium were reduced by half when the new transfer coefficients were used [Bergman et al., 1979]. The exchange of radium between sea water and sediment greatly affected the global collective dose. Exchange between the water of the oceans and their sediments might be estimated roughly on the basis of the retention times in the ocean of stable isotopes of chemical closely related nuclides among the alkaline earth metals such as strontium. Such estimates were, however, highly uncertain. A more precise estimate can be obtained by assuming that the radium concentration in water is constant and that the transfer from water to sediment is equal to the inflow and generation of radium. For this calculation the radium inventory in the oceans, the amount of radium entering the oceans through runoff, the amount generated indirect by decay of the uranium present in the oceans, and the loss through physical decay of radium itself are needed [Bergman et al., 1979]. With the latter derivation of the transfer from ocean to sediments as a basis for the calculations, the collective dose to the world population which was obtained was only 1/20th of that obtained with the previously used estimate.

The relevance of the model in a long-range perspective

The local ecosystem in particular can, over the time spans covered by the forecasts, undergo changes which have considerable effects on the exposure situation. The design of the model made it possible to analyse the consequences of important changes, such as the drying-up of the lake which constituted the primary recipient for material leached from the repository. The drying-up of large areas of the Baltic Sea might also be taken into account. In both cases, the change can give rise to additional exposure pathways through the use of the sediments for agricultural purposes.

Some elements were enriched to relatively high levels in the lake and Baltic Sea sediment. In the case of the radioactive nuclides which dominated the exposure to the critical group or the collective dose to the population, the drying-up of these bodies of water and the change of the exposure pathways did not lead to any increase of the annual doses, since the uptake of nuclides in agricultural products cultivated on the sediment did not compensate for the elimination of fish as a exposure pathway. The nuclide Cs-135 was an exception, though. Individual doses, through internal and external exposure of the population living in that area of the Baltic Sea that may be dried up, may become up to one order of magnitude higher than the doses from the calculations based on an unchanged Baltic Sea. The contribution to the collective dose from the Baltic Sea area was, however, less than one-fifth of the total dose. A higher exposure of a future Baltic Sea population through Cs-135 would therefore lead to a doubling of the total dose commitment in the long run.

A future increased utilisation of the food resources of the oceans might cause a shift towards a marine diet. Overexploitation of traditional fish populations has led to a search for other sources of nutrition from the sea. In addition to an increased utilisation of fish species that have formerly not been fished, there are large nutrient reserves in the form of squid and krill. Algae, e g kelp have been used in many countries for a long time.

Potential catches of krill may suffice for an annual consumption of 5 - 10 kg per capita on the average over a population of 10^{10} persons. Great technical difficulties exist in catching these shrimp. There is little possibility of using plankton as a food source within the foreseeable future. The importance of macroalgae as a food source will increase, however.

If, assuming no change in the amount of protein in the diet, 10 kg meat are replaced in the future by 10 kg krill or algae, the increase in uptake and dose will be limited to a factor of 1- 3 for most radionuclides. The global collective doses from isotopes of Pu and Am especially may increase by a factor of 10 - 20 for krill and by a factor of 100 - 150 for algae, still assuming 10 kg. However, the global contribution to the collective doses in the inland alternatives (which yield doses which are several orders of magnitude higher than in the Baltic Sea alternative) is less than one percent. This yields a maximum increase by a factor of 3.

In one technical report [Bergström, 1981], an analysis was performed for some selected radionuclides on how the calculated doses were influenced by variations of the parameter values. The values used to describe some major processes were varied by a factor of five up and down. The results showed, as expected, that lake water retention times affected the dose directly. An intensified irrigation also increased the doses. Changing migration rates of the radionuclides in soils affected the doses differently due to the properties of the radionuclides. Changing transfer rates to the sediments gave minor changes in doses.

2.3 KBS-3 (1983)

2.3.1 Scenarios, model design and exposure pathways

The design of the intermediate and global zones in the model system used in the KBS-3 safety analysis was the same as in KBS-2, except that the sediments were represented by additional reservoirs (see Figure 2-4) making it possible to simulate sediments partly acting as sinks [Bergström, 1983]. Soils were also represented by additional compartments. The regional zone was illustrated by using data from five different recipient areas in Sweden, leading to various numbers of compartments for representing them. Unit releases of the radionuclides were performed for these areas leading to that the area Fjällveden was selected when performing results for the safety analysis by using calculated releases in the dose assessments [KBS 3, 1983). This was because the low turnover time of water in this lake lead to higher exposures than for the other areas. The compartment system used is shown in Figure 2-4.

The modelling performed for KBS-3 also used the compartment principle which implied solving of first order differential equations with the BIOPATH code. A literature survey was performed before doing the modelling in order to obtain pertinent rate constants and values for the biological uptake of radionuclides in the aquatic and terrestrial environments [Bergström & Wilkens, 1983]. Specific expressions were used in order to obtain the rate constants in contrast to previous analyses. These expressions included general as well as specific data, some of which are still in use in similar studies, e.g. [BIOMOVS II, 1996b and Bergström et al., 1999]. However, also here the main processes of radionuclides in the biosphere were related to water turnover and accumulation. The latter was described by the K_d factor approach, which describes the relation between concentration of an element in solution and adsorption on particulate matter at steady state. Transport of radionuclides by biological material was not included explicitly.

2.3.2 Data

In similarity to the earlier assessments the same volume was used for the well while data for the surface water were taken from Sundblad & Bergström [1983]. The large well volume was justified according to studies of groundwater flows [Neretniks & Rasmusson, 1983 and Thunvik, 1983].

2.3.3 Results

Doses were reported for unit releases of activity for nuclides for the different areas, as well as for source terms based on calculations of different release scenarios from the repository.

The resulting doses (see Figures 2-5 to 2-7 and Table 2-1) for the KBS-3 study were generally higher than from KBS-2 and KBS-1. The main explanation for these results was the long turnover time for water in the lake used in the different calculated release scenarios. This emphasises the importance of site-specific data in order to be able to make reliable dose estimates.

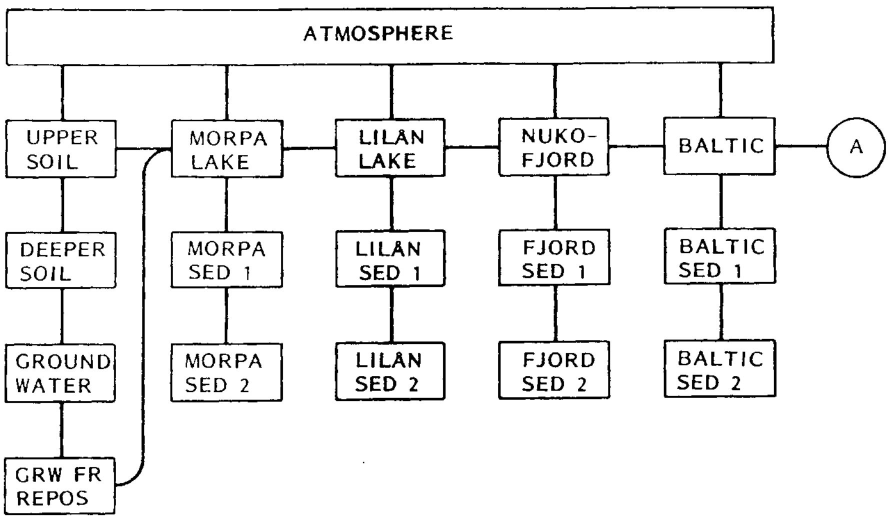


Figure 2-4 *The compartment structure used for the local, regional and intermediate source when calculating individual doses for the release scenarios analysed in KBS-3.*

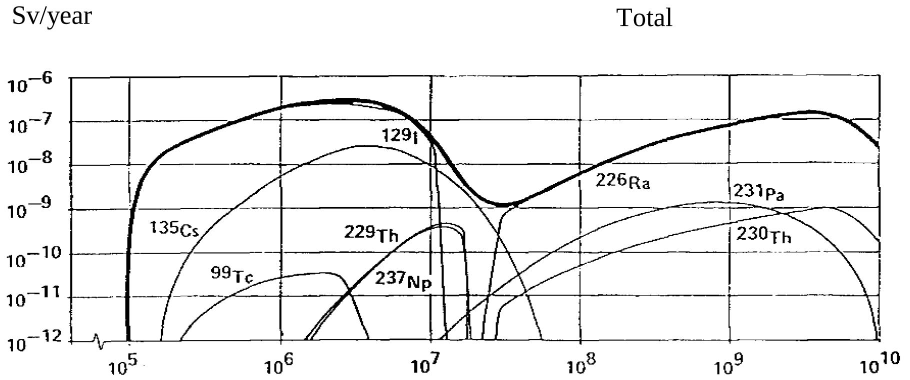


Figure 2-5 *Calculated individual doses from exposure via a well for release scenario A (Central case). This case corresponds to a degradation of all canisters from 10^5 to 10^6 years.*

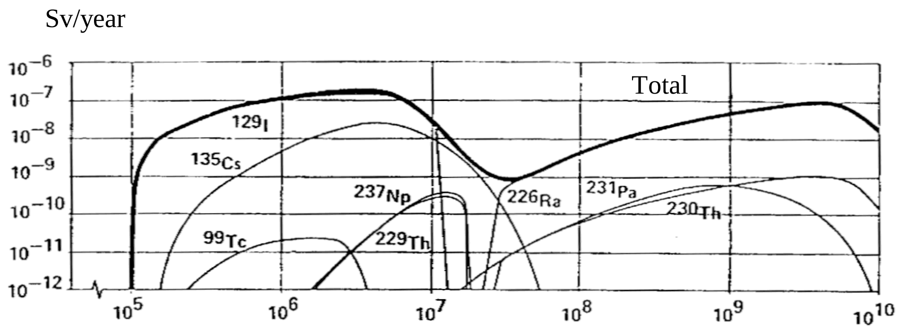


Figure 2-6 *Calculated individual doses from exposure via a lake for release scenario A (Central case). This case corresponds to a degradation of all canisters from 10^5 to 10^6 years.*

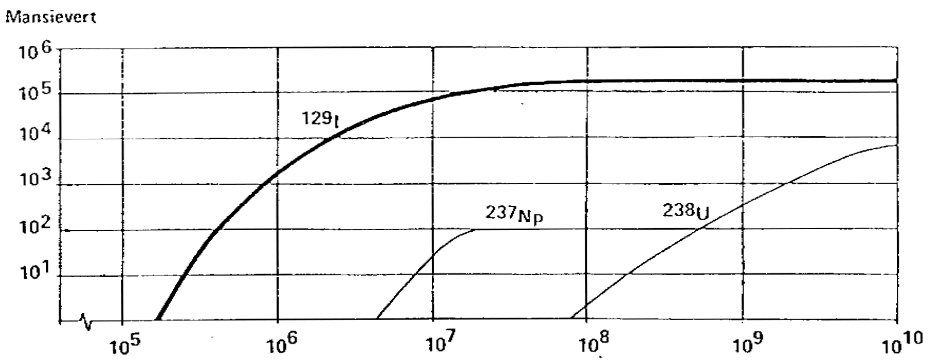


Figure 2-7 *Calculated accumulated collective dose (manSv) for release scenario A (Central Case). This case corresponds to a degradation of all canisters from 10^5 to 10^6 years.*

Table 2-1 Calculated doses due to flow of nuclides to the biosphere for the central case.

	Max ind. doses (Sv/year)		Max coll. doses (manSv/year)
Nuclide	Well	Lake	Coast
Zr-93	3.0E-13	3.0E-13	8.9E-12
Tc-99	2.9E-11	2.2E-11	2.5E-8
I-129	2.1E-7	1.8E-7	1.0E-2
Cs-135	2.2E-8	2.2E-8	1.8E-6
Ra-226	1.0E-7	7.4E-8	6.4E-7
Th-229	3.0E-10	2.3E-10	8.4E-8
Th-230	7.4E-10	8.4E-10	1.4E-7
Pa-231	1.2E-9	4.4E-10	1.8E-8
U-233	2.2E-11	1.2E-11	1.8E-8
U-234	3.0E-10	1.8E-10	1.1E-6
U-235	4.1E-12	1.6E-12	1.4E-8
U-236	7.4E-13	3.3E-13	2.5E-9
U-238	2.7E-10	1.6E-10	1.0E-6
Np-237	3.9E-10	3.0E-10	9.2E-6

In Figure 2-8, the calculated doses are compared with doses due to the natural background radiation as well as operational limits for Swedish nuclear power plants.

2.3.4 Reliability of the model

In similarity to KBS-2 the accuracy of the model predictions were discussed, see section 2.2.5. In addition to these more general discussion a Monte Carlo calculation was performed for the transfer of Ra-226 to milk due to contamination of vegetation, root-uptake and retention of irrigated water on plants' surfaces, assuming a constant level in water. The regression analysis performed showed that the transfer factor to milk dominated totally the uncertainty.

Screening calculations were also performed for some radionuclides assuming a discharge of the contaminated groundwater to a peat-bog. The peat was assumed to be used for agricultural purposes with a mixing of 90 % with uncontaminated soils. The calculations showed that somewhat higher dose than those related to exposure from a well.

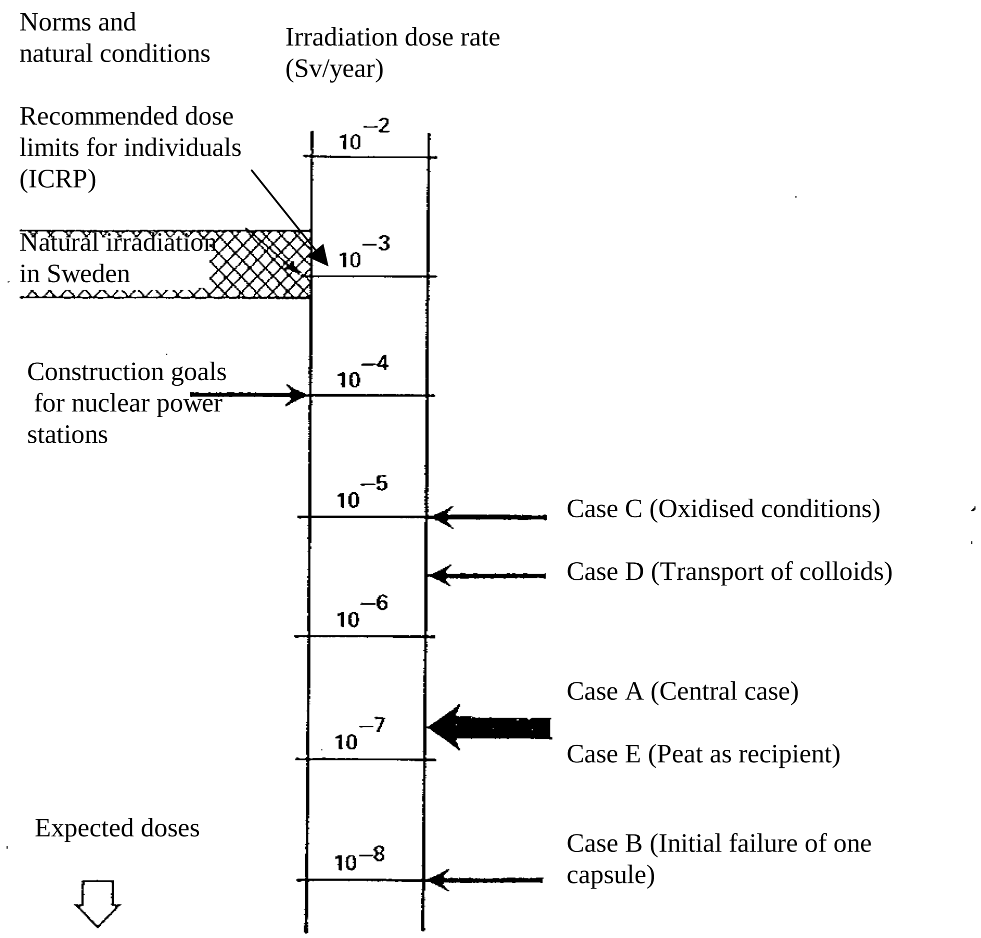


Figure 2-8 *Calculated dose rates in different scenarios for leakages of radionuclides from a deep repository. Recommended limits and natural background radiation as well as construction goals for nuclear power plant are also shown for comparison.*

2.3.5 Collection of experimental data

The work performed during 1982 - 1983 was closely co-ordinated to the evaluation needs in the KBS-3 report. Thus, the biosphere investigations were concentrated to areas where the geological and hydrological characteristics were found to be suitable for a possible repository siting.

Two major studies on the natural levels of radioactivity were reported in 1982/83. Three uranium rich springs in northern Sweden were investigated [Ek et al., 1982], see Section 5.5. The uranium and radium concentrations during different seasons were measured in spring water, peat and sediments together with data on the springs and their environment, and the concentrations of the major anionic and cationic constituents of the spring water. Investigations of the distribution of uranium, thorium and radium in soil, plant material and drainage water of agricultural lands were also carried out [Evans & Eriksson, 1983], see Section 5.6. The chemical and physical characteristics of the soils were determined. Both studies were part of an effort to build up a basis of information on the behaviour of natural radioactive elements in environments typical for Sweden.

During late 1982 and early 1983 the emphasis of the biosphere studies was shifted over to site specific data from sites under study in the geological site investigation program. In two reports, descriptions of the recipient areas [Sundblad & Bergström, 1983] and the radioactivity levels in surface waters, soils and sediments [Evans et al., 1982] were presented for the Fjällveden, Svartboberget, Gideå and Kamlunge sites (for location, see Figure 5-1). This was made in order to obtain a realistic database for the biosphere model used in the safety evaluations.

Other data used in the calculations of nuclide intake are presented in [Bergström & Wilkens, 1983]. That report discusses and defines the transfer factors, the concentration and distribution factors, the land use and yield values, and the diet and consumption rates used in the compartment model on which the BIOPATH code was applied in the KBS-3 evaluations. In Johansson [1982], the biological factors of relevance for the transformation of intake to absorbed dose are reviewed for isotopes that were of special interest for the long-term effects.

For the rest of this decade, the biosphere was mapped in all the areas that were selected for geological site investigations. The mapping included data on the radioactivity in surface water and soil and a characterisation of the ecosystem at hand. Efforts were made to evaluate the effect on dose calculations of possible changes of the ecosystem with time.

2.3.6 Comments from authorities concerning KBS-3

During 1984 several comments concerning the KBS-3 study were presented. Some important conclusions drawn from these ones are summarised hereafter.

Comments from the National Radiation Protection Board (NRPB)

National Radiological Protection Board, NRPB, was applied to analyse the KBS-3 study [NRPB, 1984]. There comments about the compartment model approach used were that this is used by most organisations in radiological assessments of geological disposals. Such models were found suitable for predicting maximum individual and collective doses, and the structure of the model was sound in that no important environmental reservoirs or exchanges appeared to have been omitted. That the biosphere did not change in time was, however, found unrealistic. An analysis of the sensitivity of results to changes in transfer rates and compartment sizes should have been carried out, in order to scope in the range of possible radiological impacts.

Another aspect that was commented was that no detailed treatment of the probabilities of the scenarios, and the risks of inadvertent human intrusion into the repository in the future had been evaluated.

NRPB concludes that the report in many respects sets standards for others to follow and that “none of the criticism in the review were of sufficient gravity to invalidate the general conclusion of the KBS-3 report, that spent nuclear fuel can be disposed of in a way that satisfies the requirements of radiological protection" [NRPB, 1984].

Comments from the Swedish Radiation Protection Institute (SSI)

SSI examined SKBF's basic material to the nuclear power companies application for loading of Forsmark 3 and Oskarshamn 2 with nuclear fuel according to the law about provisions concerning nuclear technical activity [SSI, 1983]. SSI found in general that the conditions stated in the law concerning treatment and final storage of burned fuel from a dose point of view were fulfilled. There were, however, some remarks concerning the modelling of the activity transport in the biosphere which was not complete as follows:

- No validation of the biosphere model has been performed.
- The big span of possible values of concentration and transfer factors, which exist in the nature gives uncertainty in the calculated results. This was not analysed.
- An analysis of the dynamic of the catchment area was not carried out.
- Influence from future changes in the nature such as overgrowth of lakes was not considered.
- The sedimentation process and the influence on the retention time in the biosphere are poorly understood. The influence of this was not discussed.

SSI was also of the opinion that the compartment model simulating the transport of the activity in the biosphere was applied for too long time-periods. The results were considered to be uncertain already after some hundreds of years and after next glaciation period the dose calculations have no meaning.

2.3.7 Conclusions

Overall view

The KBS-3 report represented an achievement in compiling and presenting a detailed assessment of the radiological impact of disposal of spent nuclear fuel. In many respects, it set standards for others to follow, particularly concerning the clear presentation of a complex study. Inevitably, with a study of such length and detail, a number of criticisms can be made of the methodology, models and parameter values used in the assessment. However, none of the criticisms in the NRPB review were of sufficient gravity to invalidate the general conclusion of the KBS-3 report, i.e. that spent nuclear fuel can be disposed in a way that satisfies the requirements of radiological protection.

SSI was of the opinion that the KBS-3 method for final storage of burnt nuclear fuel, proposed in the application, was acceptable concerning the irradiation protection.

Methodology

Because the KBS-3 report is a broad technical feasibility study, rather than a detailed evaluation of a specific repository design for a defined site, the methodology used was a justifiably simple one. Scenarios likely to give the most serious consequences were selected, and individual and collective doses were evaluated. However, there was no detailed treatment of the probabilities of the scenarios, or of the uncertainties in the results, and the risks of inadvertent human intrusion into the repository in the future were not evaluated.

The biosphere model was based on solving of first order differential equations, which is commonly used in radiological assessments of waste disposal options. However, the modelling did not allow for changes in the environment over long time periods.

The BIOPATH code

The BIOPATH code, which is referred to several times in this report and applied on several models, has been verified (see Section 6.3) and models built with the code have been validated in many contexts (see Section 6.2). At the time of the KBS-3 report [KBS-3, 1983], the code did not include uncertainty analysis. The largest uncertainty might be in the choice of parameters and their values. If only deterministic values are used, it is difficult to judge the uncertainty in the result. There are at present codes [Gardner et al., 1983], which are able to take distributions of parameter values into consideration, which in turn directly gives the possibility to judge their respective influence on the final result.

Suggestions for future research after scrutiny of the KBS-3 report
According to [Olivier et al., 1984] there is clearly a need for more detailed, site specific research, in order to produce an assessment which will form an adequate basis for a final decision on the disposal of spent nuclear fuel. In addition, there are some methodology and modelling topics on which KBS should carry out further work:

1 In several countries, there is work in progress to develop methodologies for comprehensive risk assessments of solid waste disposal. These methodologies will take into account the probabilities of occurrence of various possible scenarios, and will produce estimates of the uncertainties in predicted risks and doses. It is important that SKB take note of these international developments and begin to improve their own methodology (which has remained unchanged since KBS-1) along lines which are consistent on long-term radiological protection objectives for waste disposal.

2 The KBS-3-model needs to be modified to handle parameters which vary in time, and to include all the actinide daughter products. There is also a need to review the assumptions and parameters used in modelling radionuclide-sediment interactions in local, regional and global water bodies, and to incorporate more recent dosimetric data.

2.4 WP-cave (1989)

WP-cave is a possible design of a bedrock repository in which a “hydraulic cage” is constructed inside which the radioactive waste is kept. This implies that the groundwater flow is led around the cage thus greatly reducing the transport of radionuclides out of the cage in case of canister failure. Within the safety study for the WP-cave concept a modelling of two biosphere recipients were performed to address the doses to critical groups and the uncertainty of these doses [Bergström & Nordlinder, 1988, 1989a and 1989c]. The BIOPATH and PRISM codes were used. The two biosphere receptors were a well and a lake with release rates taken from separate transport modelling [Moreno et al., 1989 and Björklund et al., 1989]. Parameter values were taken mainly from the KBS-3 study and later revisions [Bergström et al., 1986]. The nuclides dominating the dose were found to be C-14, Se-79, Sn-126, I-129, Pa-231, Th-229 and Np-237 with maximum doses of about 5 μSv/year. The uncertainty for the well case was totally dominated by the mixing volume of water in the well. The factor giving second highest contribution to uncertainty was the drinking water consumption rate. The uncertainties in the lake case were dominated by the sedimentation rate, the consumption of and the uptake of radionuclides in fish and by the migration in soil.

The WP-cave concept is at present not considered as a design for a Swedish repository for spent fuel.

3 Safety analyses for the low and intermediate level waste repository

SFR, the Final Repository for Radioactive Operational Waste, is located on the coast near the Forsmark nuclear power plant, about 100 km north of Stockholm. It consists of a system of tunnels, located about 50 m below the seabed. The depth of the water is at present about 6 m. The planning of SFR started in 1980, and the first blast for construction of the tunnel was made in 1983.

The biosphere was handled in a study of incidents during the management before deposition in the repository [Bergström et al., 1981], and in the safety analysis for leakage from waste after closure of the repository, SFR-1, in 1987 [Bergström & Puigdomènech, 1987].

3.1 Safety analysis for management of radioactive waste

In Bergström et al., [1981], "dose factors" in Sv/Bq were presented, as a result of turnover in the biosphere due to incidents during the management before deposition in the repository. The values thus obtained may be used to assess consequences from releases from three types of incidents:

1 Transport accident at sea.
2 Fire in a cask.
3 Mechanical damage to a container while depositing.

A region out to 150 km distance was used for computing the collective dose in the first two cases. Only doses to personnel were treated for mechanical damage, which is therefore not reviewed in this report.

3.1.1 Transport accident at sea

In the first case, the ship carrying the casks was assumed to be damaged, which leads to deformation of casks and subsequent release of 1 Bq of each nuclide to the seawater. Three scenarios were considered: release for 24 hours, 6 months and continuously, respectively. Dispersion in the seawater was modelled, as a plume in the first two cases, and with a compartment system in the last. The only considered exposure pathway was consumption of fish, because it had shown to dominate the dose. Individual dose and collective dose commitment due to consumption of fish were calculated for Co-60, Sr-90, Cs-134 and Cs-137. Overall, the Cs isotopes contributed most to the doses.

3.1.2 Fire in a cask

The fire in a cask was assumed to lead to a release of Co-60, Sr-90, Cs-134 and Cs-137 to the atmosphere from the stack during 1 hour. Exposure pathways for direct exposure were external dose from the cloud, external dose from radionuclides deposited on the ground, and inhalation. In addition to those, doses via consumption of vegetables, milk and meat were calculated. Sr-90 gave the largest contribution to the direct dose, while the Cs isotopes dominated the doses from consumption. The collective dose commitment, integrated over 500 years, was dominated by consumption of cereals, followed by that of milk.

3.2 SFR-1 – Safety analysis for the repository after closure

The safety analysis for leakage from waste after closure of the repository, SFR-1, was published 1987 [SSR, 1987]. The part pertaining to the biosphere was based on Bergström & Puigdomènech [1987], where model descriptions and results are given. The results from FSAR [SSR, 1987] and the review from the authorities lead to a study, dealing explicitly with the problems of C-14, cf. Section 6.2.3. [Hesböl et al., 1990]. In the revised FSAR, [FSA, 1991] the results from [Bergström & Puigdomènech, 1987] were used with an extension of the well scenario.

Below follows a review of the environmental impact study for SFR-1.

3.2.1 Safety assessments and base scenarios

Two main scenarios were handled; one for leakage of the nuclides directly to the coast (brackish scenario), and one where the releases occur to an inland area after land-rise. The biosphere was modelled using compartment theory, where the biosphere components were divided into physical areas with uniform properties. The exchange of nuclides between those compartments was described by rate constants expressed in turnover per year, also taking into account radioactive decay.

The main purposes with the analysis were to assess the radiological consequences to a critical group and population due to potential releases from the repository. The model was therefore divided into four spatial zones, as in the KBS studies, to be able to simulate the turnover of the radionuclides from the local to the global area. The four scales were

- Local zone
- Regional zone
- Intermediate zone
- Global zone

The local zone was used for the calculation of individual doses to a critical group living around the effluent area of nuclides to the biosphere. For releases during the first thousands years after closure, the local zone consisted of a part of Öregrundsgrepen. Thereafter the zone was assumed to consist of a well and a lake area as a consequence of land rise.

In **the regional zone,** which was used for calculation of collective doses**,** the dispersion of radionuclides in an expanded area around the point of discharge was considered. Recipients were the entire Öregrundsgrepen and the lake for the coast and inland scenario, respectively. The local zones were consequently included in the regional zone.

The intermediate zone was used in the collective dose calculations. It consisted of the entire Baltic Sea.

The global zone was also used in the collective dose calculations and included the entire world.

3.2.2 Model description

Model structure

Local zone

The main recipients, Öregrundsgrepen and the lake, were subdivided into compartments for water and two sediment layers (see Figure 3-1). Exchange of nuclides between these compartments due to water turnover and particle fluxes was considered.

Homogenous mixing was assumed within the compartments, which made it necessary to subdivide the sediment in two compartments. One compartment was the upper sediment (0 - 10 cm), where oxidising conditions prevail and where an exchange with the overlying water occurs. The other compartment was the deeper sediment with reducing conditions, low bioturbation and low water-exchange.

The surrounding agricultural area was divided in three compartments, where the upper layer (approx. 0 - 30 cm deep) consisted of the root zone where agricultural practices take place. The next reservoir was the soil beneath the upper surface, and the third level represented the ground water (Figure 3-2).

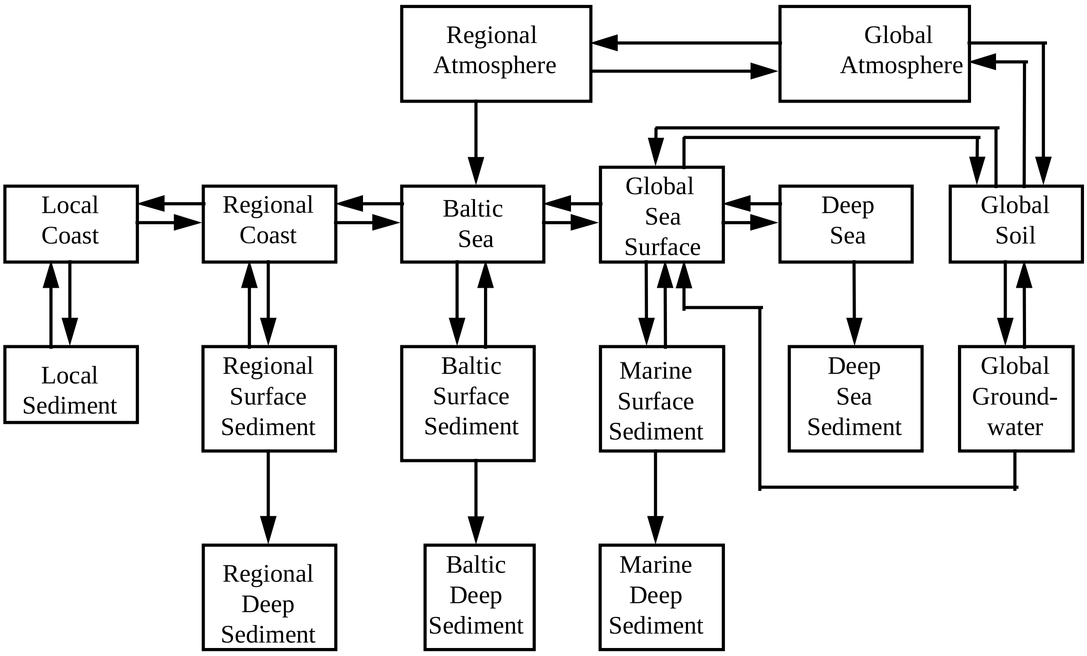


Figure 3-1 *The structure of the BIOPATH model for the coast scenario.*

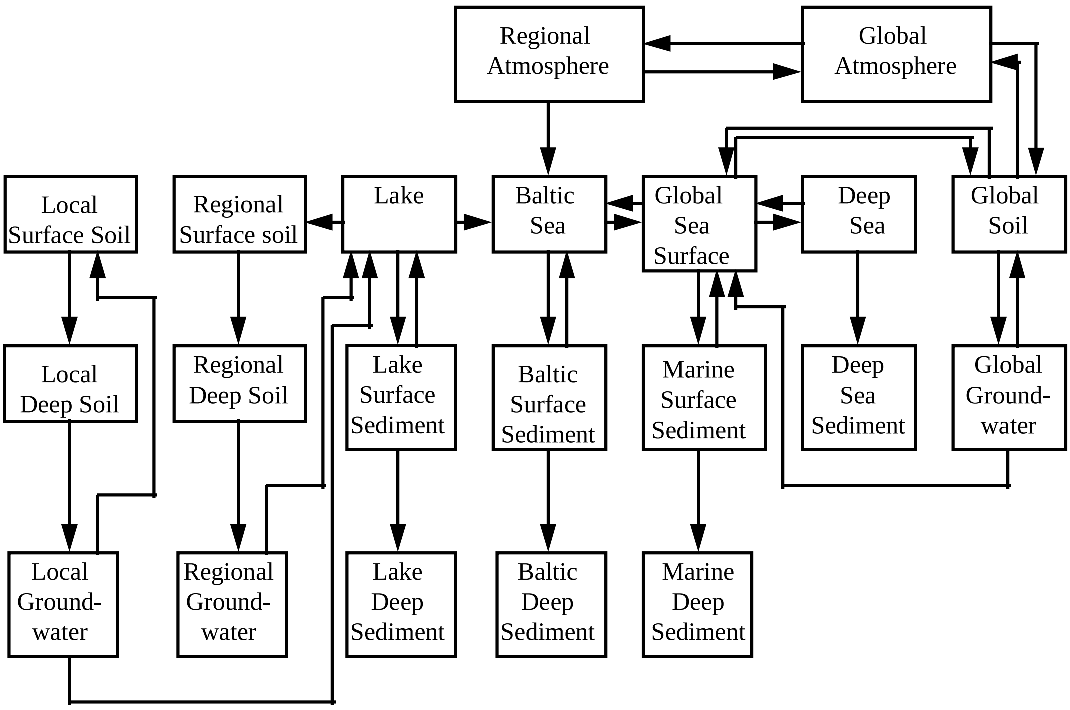


Figure 3-2 *The structure of the BIOPATH model for the inland scenario.*

Intermediate zone

The intermediate zone was not a primary recipient and consisted of the Baltic Sea and its sediment (cf. Figures 3-1, 2).

Global zone

The global zone consisted of five compartments. Two compartments was used for the water in the oceans, of which one represented the upper, well mixed, surface water down to approximately 150 m, and the other represented the deeper parts of the oceans (Figures 3-1, 2). The other compartments were the ocean sediments, global groundwater and global terrestrial soils.

Model

The exchange of radionuclides between the compartments was described mostly by nuclide-specific transfer coefficients. This lead to several first order linear differential equations which were solved numerically by the program BIOPATH [Evans, 1980 and Bergström et al., 1982]. The processes included in the models for the turnover of nuclides were as follows

- Turnover of water in all water compartments
- Transfer from water to sediments
- Leakage from upper soil to deeper soil
- Leakage from deeper soil to groundwater
- Outflow of groundwater to surface water
- Irrigation of farming land
- Resuspension from sediment to water
- Resuspension from soil (global area)
- Deposition from regional and global atmospheres

The general rate constants were obtained from water flows between compartments and, for the soil compartments, a retardation factor which was element specific. The retardation was described with K_d factors in combination with porosities and densities of the soils. The transfers to the sediments were obtained by area specific mass sedimentation rates coupled to K_d values for the radionuclides to suspended matter and actual mean depths. Resuspension from the sediments and back to water and transfer to deeper sediments were generic values in common for all elements.

Exposure pathways to individuals and population

Only internal exposure pathways were considered in the assessments. This simplification was justified from the experiences of earlier calculations of exposure from disposal of high-level waste [Bergman et al., 1979 and Bergström, 1983]. The internal exposure pathways were those connected to agricultural practices or consumption of marine products. The exposures were calculated in a traditional way [IAEA, 1982], that is by use of constant parameter values for root-uptake and transfer to milk and meat, respectively. However, all values were given with best estimate and ranges. Their applicability was also briefly commented.

Radioactive nuclides, which may occur in food, are transported into the food chains via a varying number of paths.

- Crops are subjected to radionuclides from the soil by their root system and through deposition on leaves.

- Occurrence of radionuclides in meat and milk is due to intake of contaminated food, soil and drinking water, ingested by cattle.

- Fish and other marine products absorb and accumulate radionuclides from surrounding water and through contaminated food.

Crops and marine products

The calculated uptake of radioactive nuclides in groceries was based on concentrations of radioactive nuclides in soil and water as a function of time. It was supposed that a steady-state exchange between vegetation and soil as well as between fish and water prevails. Uptake by plants through the roots and uptake by fish from water were described by nuclide-specific concentration factors. Contamination of leaves due to irrigation or deposition of resuspended material was also included.

Cattle

Animals may take in radioactivity through contaminated vegetation as well as by consumption of contaminated water and soil while grazing. The ingested nuclides are then transferred to milk and meat. That transport was described by distribution factors [Ng et al., 1977 and 1979], assuming steady-state conditions. In this way the concentration of the respective element in milk and meat was calculated from the cattle's daily intake rate of food and water.

Well

In the well scenario, radionuclides reached man through drinking water. The nuclides were also assumed to reach man via consumption of milk and meat from cattle drinking water from the well. The wells were assumed to have such a low water production that they were not used for irrigation of agricultural crops, and thus only irrigation of green and root vegetables in gardens was taken into account. It was assumed that the critical group was also exposed to contaminated fish from the lake. In addition lake water was used for irrigation of adjacent farming-land.

Lake

When the lake was primary recipient, it was assumed that the water in the lake was utilised as drinking water for both humans and animals. Furthermore, the assumption was that the lake water was used for irrigation. The exposure pathways were therefore expected to be from all foodstuffs, which was supposed to be the main part of the yearly human intake of food.

Final assessment

In the final assessment the exposure to critical group occurred simultaneously from the well and lake water in the inland scenario. The exposure pathways to critical groups considered for each case are summarised in Table 3-1, where the compartments used for calculation of the pathways of activity related to each exposure pathway are given. Cereals grown on soil irrigated with lake water were not included because of their negligible contribution to exposure compared to that from the well.

Table 3-1 The exposure pathways to critical group considered for each calculated case. The compartments used for calculating the exposure are shown for the two scenarios.

Path of exposure	Inland scenario	Coastal scenario
Inhalation	Local surface soil	
Drinking water	Well	
Milk	Well, regional surface soil	
Meat	Well, regional surface soil	
Green vegetables	Local surface soil	
Cereals	Local surface soil	
Root vegetables	Local surface soil	
Eggs	Well	
Fish	Lake	Coast
Invertebrates		Coast

Exposure pathways for the **regional zone** were considered in a similar way as for the local zone. There was, however, no exposure of the regional population through the part of Öregrundsgrepen that was the primary recipient in the coast case, or from the well in the inland case, as doses to critical group was not included in the calculations of the collective doses [Bergström & Puigdomènech, 1987]. Current values of annual yield for the agricultural area and Öregrundsgrepen were therefore utilised to calculate these doses.

The exposure pathways from the **intermediate zone**, i.e. the Baltic Sea, were through consumption of fish and algae products. Algae were considered because they may become an important protein source in the future.

In the **global zone**, all terrestrial exposure pathways were taken into account, as well as the same marine exposure pathways as for the Baltic Sea.

3.2.3 Results

With the selected calculation premises, a maximum environmental impact is obtained approximately 100 years after closure of the repository for these sections where the outward transport mechanism is attributed to groundwater flow. For the silos, where diffusion governs the outward transport, the maximum impact will not occur until about 7 000 years after closure. The size of this maximum will vary depending upon what the recipient looks like then. Figure 3-3 gives the maximum dose rates to individuals in the critical group in relation to established dose criteria.

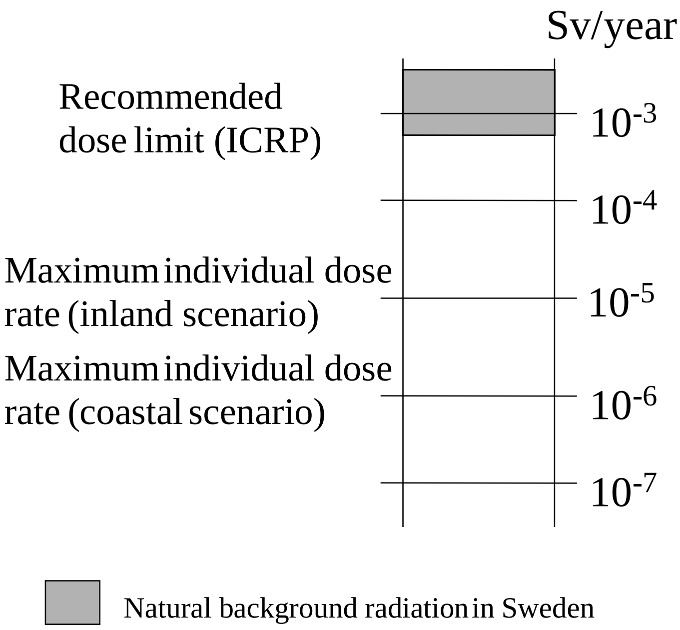


Figure 3-3 *Calculated maximum dose rates for the inland and coast scenarios in the safety analysis of SFR. Recommended dose limits and the natural background radiation are also shown for comparison.*

In summary, it can be said that even very extreme events, such as major rock movements or the drilling of a drinking water well through the repository, will give individual doses that lie within acceptable limits.

An uncertainty analysis was performed with Cs-137 for the coast scenario. Most parameters were varied and analysed with PRISM [Gardner et al., 1983]. The analysis showed that human consumption and bioaccumulation of Cs-137 in fish were the main contributors to the uncertainties in the calculated dose.

Variation analysis was performed for a well scenario. This showed that dilution volumes gave the major contribution to the variations in the dose estimates. Finally, doses for Pu-239 and Pu-240 were estimated, assuming that all released activity was trapped in lake sediments. These sediments were then used for agricultural purposes. The concentrations of elements in this soil were lower than those obtained from irrigation of soil with water from the well.

3.2.4 Regulatory review

SSI (the Swedish National Radiation Protection Institute) performed in 1988 a review of the FSAR [Bergman et al., 1988]. They concluded that the assessments corresponded to the general status of environmental modelling. However, they identified that there was no connection between surface sea and global atmosphere. This underestimated the collective dose for C-14 in comparison to the calculations performed by SSI [Bergman et al., 1988]. This error in combination with the high importance of exposure from C-14 lead to that a specific study of C-14 was initiated [Hesböl et al., 1990], see Section 3.2.5. The authorities also pointed out that realistic estimates of doses should be made.

After the in-depth analysis 1991, SSI and SKI (Swedish Nuclear Power Inspectorate) made a joint report reviewing the safety analysis [SSI, 1992]. The main comment from that review pointed out that documentation and model descriptions should be improved as well as reasons for uncertainties be discussed. However, the authorities focused considerably on location of wells, as wells were deemed to give the highest exposure.

3.2.5 Improved carbon-14 model for SFR

The well/lake scenario for C-14 release from SFR [Bergström & Puigdomènech, 1987] was modified to allow all C-14 present within the repository (8.4 GBq) to be released from the repository, dispersed and retarded in the geosphere and eventually (after 2 500 years) enter the biosphere [Hesböl et al., 1990]. The individual doses peaked at about 24 000 years after repository closure at 5 nSv for the local zone and 0.8 nSv for the regional zone. The global collective dose commitment was estimated to 1.1 manSv. Owing to the long half-life of C-14, however, compared with the environmental flux rates of carbon, the collective dose commitment, integrated over infinite time, is not affected by the manner in which C-14 is discharged. New data for the inventory in and release from the repository had shown that the release rate was about 100 times lower than that considered earlier, cf. Section 3.2.3. This lead to about the same collective dose commitment, although the model was corrected and gave a higher commitment per release rate.

In the local zone, consumption of vegetables and water contributed with 41 and 27 % to the dose, respectively, while fish consumption dominated the dose in the regional zone.

4 SKB-91

The purpose of the biospheric part of the special safety study SKB-91, [SKB, 1992], was to estimate dose conversion factors based on unit releases of long-lived nuclides from a repository into the biosphere. SKB-91 did not in general deal with the uncertainties in the biosphere, but used a set of dose conversion factors (see Table 4-1) and the release rate from the geosphere far field to calculate dose to individuals in a critical group. These dose conversion factors apply to a relatively conservative situation that gives high doses but still has a high probability of occurring subsequently within the studied time scale. Three cases were studied, one central case with radionuclides reaching biosphere via a lake and partly via a well, one with all radionuclides reaching the well, and one case where the Baltic sea was recipient.

4.1 Model design

The standard local biosphere of the central case consisted of a well and a lake with adjacent farming land [Bergström & Nordlinder, 1990b, 1990c 1991a]. It was assumed that a fraction of 1 % of the radionuclides reached a well directly, while the remaining part was diluted into lake water (see Figure 4-1). A compartment model was devised, and ten exposure pathways originating from radionuclides in well and lake water were considered (see Figure 4-2). The ecosystem, diet and living habits were assumed to be constant and representative for current conditions in Sweden. No delay or reduction of radioactivity due to accumulation in the interface between the geosphere and the biosphere was considered. The BIOPATH code was used for solving the first order linear differential equations and calculating the doses for adults and five year old children, respectively.

Additional processes were included in these models compared to the model used in the KBS studies. These are diffusion in sediments and transfer of radionuclides from well water to soil due to excretion of radionuclides from animals drinking well water containing radionuclides. Other changes were that resuspension rates from water to sediments were increased considerably according to information obtained from field studies, see Section 5.3.

Another major difference was that the calculations were performed for a time period of 500 years during which no fundamental evolution of the biosphere was expected. The time period was also considered to be plausible for irrigation activities.

The pathways for ingestion of nuclides were assumed to be via different types of food and drinking water. The intake of soil was also included to account for e.g. consumption of incompletely washed vegetables. This intake was assumed to be to 0.01 kg/year mainly from the garden plot.

Earlier calculations e.g. KBS-3 [Bergström, 1983] of the doses from the long-lived nuclides showed that the internal exposure dominates the exposure for the nuclides considered. The only external exposure considered was radiation from ground i.e. from the fields and the garden plots.

Initially only releases to fresh water was assumed while in a later report [Bergström and Nordlinder, 1991a] calculations were also performed for a generic coastal area. Doses were also calculated from naturally occurring radionuclides in Baltic Sea water.

4.2 Data

In contrast to the earlier studies the volume of the well was solely determined on the basis of annual demands of water for humans and their cattle. This lead to lower volumes than the ones used earlier. All calculations were performed with uncertainty analyses.

4.3 Results and conclusions

SKB-91 was finalised during 1992. Conversion factors to be used in combination with calculated releases, are presented in Table 4-1 as arithmetic means of the calculated distributions These values do not consider any contributions from daughter nuclides in the biosphere. Such contributions were only notable for Zr-93 and Th-229. If they were to be included, the conversion factors would increase with 7 and 36 %, respectively.

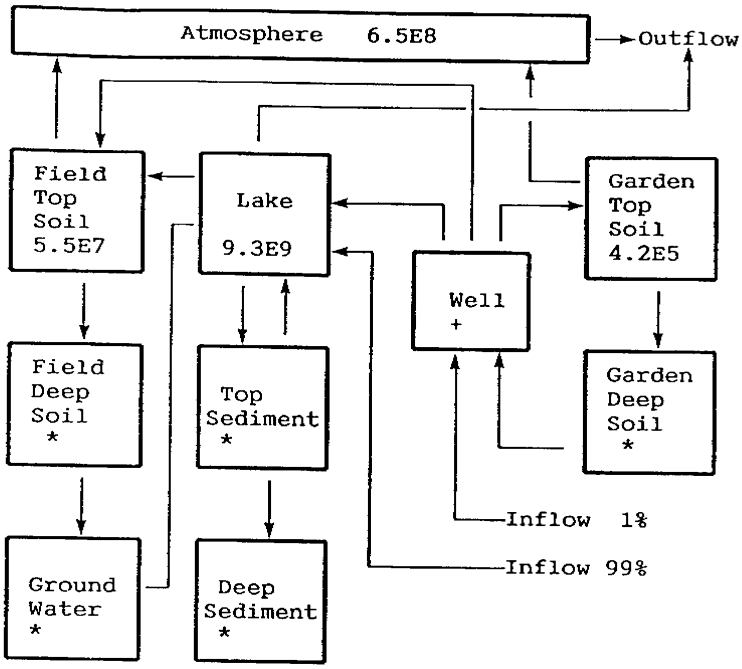
The drinking water from the well was shown to be the dominant pathway for most nuclides.

The uncertainty in the results due to the uncertainty in input parameter values were examined using the PRISM code system, and reported in [Bergström & Nordlinder, 1991b]. The main conclusions were:

The actual dilution in groundwater was of great importance when estimating possible exposure from long-term leakage of radionuclides from spent nuclear fuel. For nuclides with high bioavailability, however, exposure from dispersion of radionuclides into lake water may give rise to higher doses than from groundwater. In lake ecosystems, the most important processes for decreasing activity in the water is, for mobile nuclides, the turnover of water, and for immobile nuclides, the adsorption to suspended matter and the transfer of this material to the sediments. The factors contributing most to the uncertainty in the results are those related to the turnover of nuclides within the ecosystem. Consequently, the doses were not so sensitive to variations in exposure pathways as to the nuclide behaviour in the biosphere in general.

Table 4-1 Dose conversion factors (Sv/Bq) for unit releases of all radionuclides to a well, 99 % to a lake and 1 % to the well, or all to the Baltic Sea.

Nuclide	Well	Lake 99 %, Well 1 % (Central case)	Baltic Sea
C-14	4.2E-13	1.3E-14	3.5E-17
Cl-36	2.0E-13	2.0E-15	2.0E-18
Ni-59	8.0E-14	8.0E-16	2.0E-19
Se-79	5.4E-12	6.3E-14	2.9E-16
Sr-90	2.2E-11	2.2E-13	8.2E-18
Zr-93	2.7E-13	2.7E-15	5.9E-19
Tc-99	1.7E-13	1.7E-15	1.8E-19
Pd-107	7.0E-14	7.0E-16	2.0E-19
Sn-126	3.1E-12	3.7E-14	3.8E-16
I-129	4.9E-11	5.4E-13	4.1E-16
Cs-135	1.6E-12	3.9E-14	1.1E-17
Cs-137	8.6E-12	2.4E-13	6.1E-17
Ra-226	1.8E-10	1.8E-12	7.2E-16
Th-229	6.0E-10	6.0E-12	2.0E-15
Th-230	7.5E-11	7.5E-13	1.9E-16
Th-232	4.0E-10	4.0E-12	2.0E-15
Pa-231	1.0E-8	1.0E-10	2.0E-14
U-233	1.6E-10	1.6E-12	4.3E-16
U-234	1.6E-10	1.6E-12	4.2E-16
U-235	1.5E-10	1.5E-12	4.0E-16
U-236	1.5E-10	1.5E-12	4.1E-16
U-238	1.4E-10	1.4E-12	3.8E-16
Np-237	2.2E-10	2.2E-12	5.9E-16
Pu-239	4.3E-10	4.3E-12	4.2E-16
Pu-240	4.3E-10	4.3E-12	4.2E-16
Pu-241	7.9E-12	7.9E-14	7.9E-18
Pu-242	3.9E-10	3.9E-12	3.7E-16
Am-241	4.1E-10	4.2E-12	7.8E-16



* Not of importance for the results
\+ The volume is varied within the calculations.

Figure 4-1 *Structure of the compartment model of the studied biosphere with masses indicated. The inflow values (1 and 99 % respectively) are valid in the central case.*

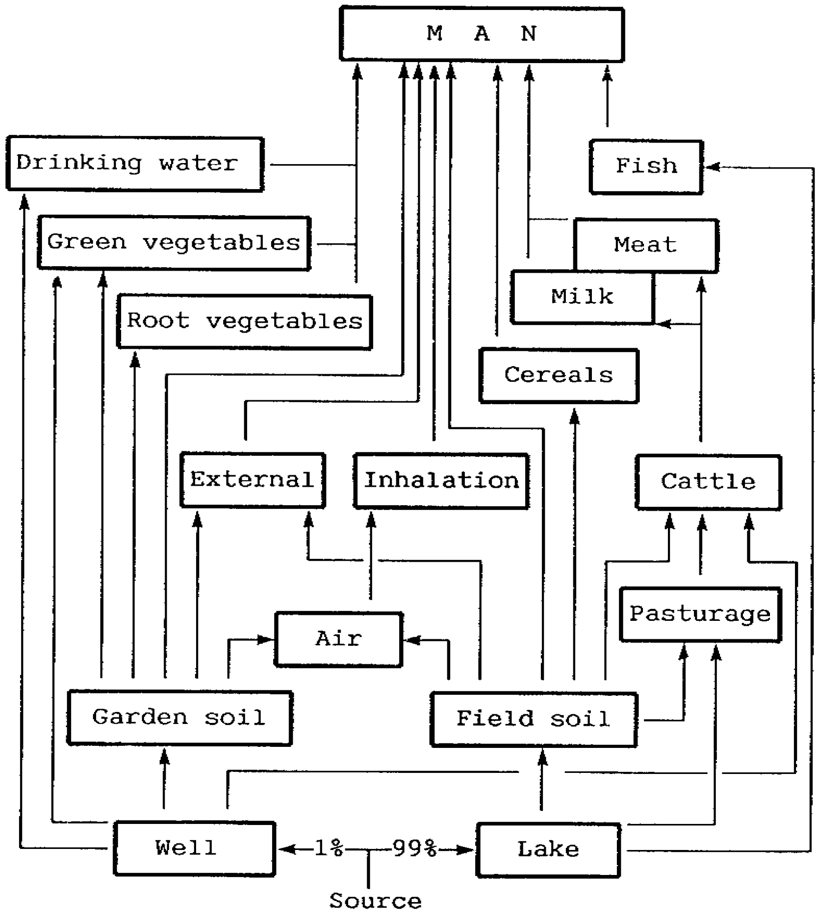


__Figure 4-2__ Model structure for dispersion and calculation of exposure to humans. The source values (1 and 99 % respectively) are valid in the central case.

5 Experiments and environmental data

Experience from the biospheric safety analyses described above indicated, among other things, the need for more data about physical and chemical processes in a long-term perspective. Several field studies were therefore carried out, from 1980 and onwards, for naturally occurring radionuclides. In addition some site specific studies were performed. Figure 5-1 shows the locations of sites for studies.

***Figure 5-1** Study areas mentioned in the text.*

5.1 Th-229 in shore sediments (1980 - 1981)

In the dose assessments performed for KBS-2, the doses from Th-229 were totally dominated by external exposure. A study was therefore initiated to investigate this nuclide. Exposure from the Th-229 in shore sediments was reported in Edvardsson & Evans [1981]. Field measurements at Studsvik (see Figure 5-1) indicated a rather homogeneous distribution of thorium in shore material at the level of around 20-40 Bq/kg. Calculations of dose conversion factors were made, yielding values ten times higher than those of KBS-2.

5.2 Uranium and radium in Finnsjön (1980 - 1981)

In Evans & Bergman [1981], equilibrium levels of uranium and radium in soil, groundwater, lake water and lake sediment in the lake Finnsjön in Sweden (see Figure 5-1) were studied in order to establish transfer factors for the elements between these environmental constituents. The results gave transfer factors between soil and lake water that were around 100 times lower than those previously used in KBS-2. This revealed the need for more data on background levels of naturally occurring radioisotopes in various environments, in order to make more reliable estimates of transfer factors.

Consequently, several studies were started during 1980 in order to extend the database on uranium and radium, cf. Sections 5.3-5.6.

5.3 Uranium, radium and radon in wells (1980 - 1981)

In Aastrup [1981], uranium, radium and radon levels in 42 wells that form part of the so-called “groundwater network” in Sweden were reported. Within this network, data on undisturbed groundwater was gathered from 85 areas all over the country. Observations concerning such factors as groundwater level, water chemistry and temperature had previously been collected during a 10 - 20 year period in order to shed light on the natural pattern of variation.

The results, sorted according to bedrock and aquifer type, are presented in Table 5-1. They essentially showed agreement with previously reported values for natural background levels [KBS-2, 1978].

Table 5-1 The aquifer concentrations of uranium, radium and radon in wells.

		Median values			
Bedrock at sampling location	Type of aquifer	Uranium mBq/l	Radium-226 mBq/l	Radon-222 Bq/l	Number of samples
Sedimentary bedrock	Soil aquifer	25	6	70	8
	Rock aquifer	7.4	2.5	25	12
Granitic and gneissic bedrock	Soil aquifer	14	3,5	68	14
	Rock aquifer	59	97	115	8

5.4 Uranium in water and sediments (1981)

SGU, the Geological Survey of Sweden, performed a study in 1981 with the purpose to study how uranium concentrations in stream water and organic material were related to various geological parameters such as rock types, average uranium content and radioactivity, fracturing, leachability of uranium from the bedrock, occurrence of uranium mineralisation and thickness and type of quaternary deposits. The effect of environmental factors such as climate, precipitation, height above sea level and topography were also considered.

The data used were taken from 14 areas selected from the geochemical prospecting performed during 1971 to 1980. The areas were selected so they should represent different geological features in the country. KBS compiled and analysed these data to study uranium distribution factors between water and sediment, and the results are published in Ek [1981]. The following conclusions were drawn from the material:

- The uranium level in water and creek peat will be high if any of the following conditions are fulfilled for the bedrock
  1. High background level of uranium
  2. High fracture frequency in the bedrock
  3. Good leachability for the uranium in the bedrock
  4. Presence of uranium mineralisation

- The uranium level in the water fluctuates due to the influence of environmental factors (such as precipitation). The fluctuations overshadow the influence of the geological environment at low levels. At higher levels, the fluctuations become less dominant and the correlation between the uranium content of the water and the uranium content of the bedrock becomes more pronounced.

- The uranium levels in water and creek peat are positively correlated at high levels, but the correlation becomes progressively weaker at lower levels. This is due to the fluctuations in the uranium content of the water, described above.

In view of these results, a greater emphasis was placed on statistics on water discharge rate and precipitation in the studies of following years.

5.5 Uranium and radium in springs (1981 - 1982)

An in-depth study of three natural springs with high radium and uranium levels and well-defined run-off areas was conducted during 1981 and 1982. In all, some 1 000 samples were collected in order to determine the uranium/radium balance in the system. The results were published in Ek et al. [1982]. There was mostly disequilibrium between the content of uranium in peat and water. The very high adsorption capacity of peat and its low leaching rate were assumed to be responsible for this discrepancy. The field data were supported by some laboratory experiments. The accumulation by peat was always much higher than the corresponding losses. The effect of freezing seemed not to be of any importance for the leaching rate. A lowering of the pH, on the other hand, affected the release of uranium bound to the peat.

5.6 Uranium, thorium and radium concentrations in soil, plant material and drainage water

The distribution of naturally occurring uranium, thorium and radium in soil, plant material and drainage water was studied [Evans & Eriksson, 1983]. Data on transport and accumulation of naturally occurring radionuclides in soil and plant material was taken from [Eriksson & Fredriksson, 1981]. Sampling and analysis of soil and drainage water from 16 research fields located in different parts of the country were also performed as well as sampling of crops from 9 of these fields.

The plant/soil concentration ratios showed that very small fractions of the nuclides were available for the plants. The uptake decreased in the following order: Ra>U>Th. The nuclide content in the drainage water generally indicated very low leaching rates.

5.7 Radioecological investigation in uranium-rich areas in northern Sweden

A radioecological investigation was carried out in two uranium-rich areas in northern Sweden where prospection work had been carried out [Pettersson et al., 1988]. The study was financially supported partly by the Swedish Nuclear Fuel and Waste Management Co. Aquatic, terrestrial and atmospheric samples were analysed, mainly for radionuclides in the uranium series. In one of the areas, about ten times higher concentrations of uranium, thorium and radium were found in lichen close to the mineralization, due to aerial dispersion. In the aquatic system, no signs of enhanced levels were observed. For the short-lived radon daughters in the air, there was no correlation between concentrations and distance from mineralization, as a result of the high natural background.

5.8 Natural development of lake ecosystems

Groundwater is considered to be the pathway for radioactive nuclides from a deep repository to reach biosphere and man. The characteristics of the groundwater recipient in the biosphere are therefore of major importance for the dispersion of radionuclides.

Development of the recipients in the biosphere is either natural or caused by man. Changes often occur in a shorter time period than the duration of a possible release from the repository, which in safety studies has been assumed to be from thousand to several hundred thousand years. Even with a constant release rate, this changing biosphere results in a variation in the radiological consequences with time.

The recipients are influenced by the various mechanism of change, for instance: by eutrophication of lakes, by creation of peat bogs, by the use of a drained lake sediments for agricultural use, or by the land rise causing change in the shore line. This will also affect the transfer of various radionuclides from biosphere to man which results in an unavoidable uncertainty in the assessment of the safety of the repository.

A quantification of the uncertainty would give a better understanding of the relevance of the dose consequence predictions, and would also indicate to what depth and detail it would be meaningful to characterise the transfer of radionuclides in the many possible groundwater recipients.

To clarify this a study was launched in early 1984. Initially, the project was divided in two phases, but a third modelling phase was added in 1986. The goal of the first phase was to identify factors and parameters of importance for the radiological consequences in a normally evolving biosphere, and to recommend an area where to investigate these parameters by sampling and analysis [Agnedal et al., 1984]. The two lakes Trobbofjärden and Sibbofjärden near Studsvik were recommended for further investigations (Fig. 5-2).

In the second phase, experiments on development of lake ecosystems were made at the two lakes until 1986. Lake Trobbofjärden has been shut off from the Baltic Sea since 1955, while Lake Sibbofjärden still has an open connection through which brackish water from the Baltic Sea may pass.

The work of Phase 2 and Phase 3 is presented in Sections 5.8.1-5.8.3 and 5.8.4, respectively.

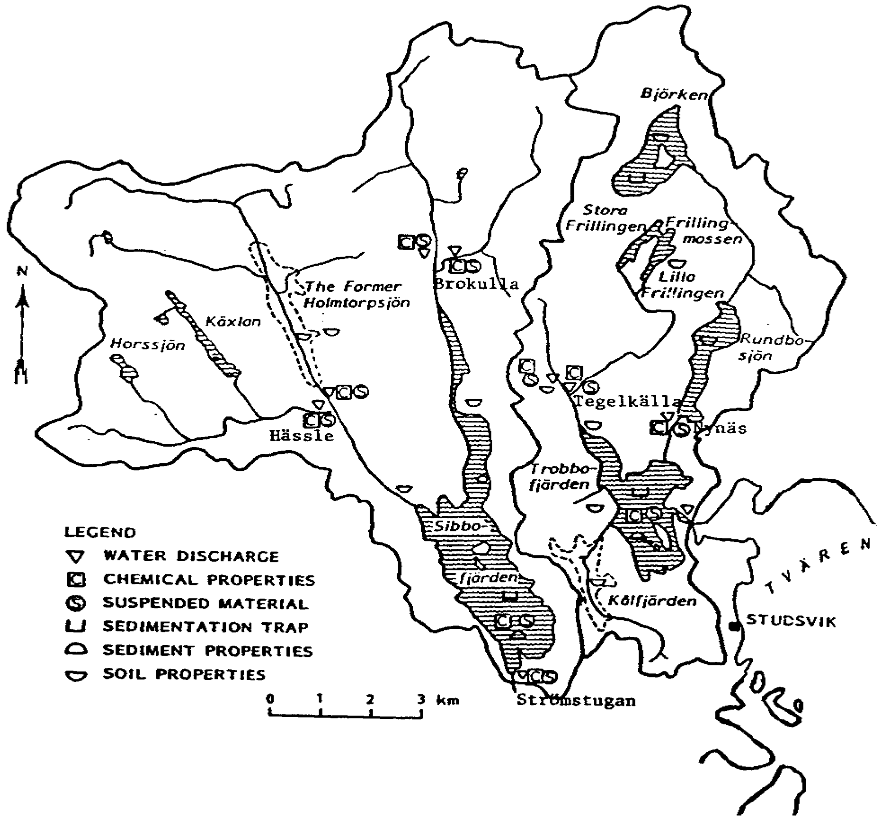


Figure 5-2 *The catchment area of Trobbofjärden and Sibbofjärden. Type of sample taken is indicated by symbols.*

5.8.1 Field studies of sediments and vegetation

Sedimentation

In order to form the basis for release scenarios of radionuclide dispersion in a lake ecosystem that gradually is silting up to become agricultural land, sediment budgets were performed for Lake Trobbofjärden and Lake Sibbofjärden. The yearly load of settled material was measured in situ during a two-year period using sediment traps at different sites and depths [Evans, 1986].

The net sediment growth, integrated over a longer time period, was on the average 2 - 4 $mm \cdot y^{-1}$. Resuspension showed to be the single most difficult factor to assess in the budget calculations, and was assumed to contribute 50 - 80 % of the sediment catch. A total silting up will occur within 1 500 - 3 000 years and 2 200 - 4 500 years for Lake Trobbofjärden and Lake Sibbofjärden, respectively.

Vegetation mapping

Mapping of vegetation was made to determine biomass production [App. 1 of Evans, 1986]. This study was performed during the summer of 1985, and showed that a decrease in salinity and in flow through the bay have influenced the composition and abundance of species of water plants and land-based plants along the shoreline.

Recipient evolution

Sampling of sediments along profiles from surrounding solid grounds to deep lake sediments was made in order to study lake sediments of different age and character [Sundblad, 1986]. Discharge measurements and analyses of macro-constituents and suspended material in water samples were made for estimation of the material and water balance of the lake.

The results from this part of the study may be summarised as follows:

- Material balance calculations showed that resuspension is one important parameter for calculations of the turnover of elements in sediment. Leakage of, for example chloride, from the Lake Trobbofjärden sediment was observed.

- The distribution of elements in sediment cores shows minor variations with depth down to at most 160 cm. The redox front is found less than 5 cm from the sediment surface.

- The quotient between the amount of elements in the solid and water phases has been found to be in the order of 1 000 to 10 000.

Data from the investigation were used in the modelling of the mobility of radionuclides during the evolution of the lake ecosystem. The relevant data was transport of suspended material, leakage from sediment, chemical composition of solid and water phase of sediment, elemental distribution between the solid phase in sediments as well as soil in relation to the liquid phase, nuclide migration in sediment cores, and biomass distribution along the shores.

5.8.2 Chemical studies

The following chemical studies were performed [Andersson, 1987]:

- Determination of pore water composition in the sediments. Parameters of importance to the mobility of trace metals such as pH, Eh, S^{2-}, ionic strength and contents of complex forms were determined.

- Characterisation of the solid sediment phase. Measurement of organic content, cation exchange capacity and in some cases surface area and mineralogy.

- Trace metal distribution between pore water and solid phase to provide information on the mobility of naturally occurring trace metals in sediments.

- The influence of organic complex formers on the mobility of trace metals. Fractionation according to molecular weight of trace metals complexes in the pore water gave information on the influence of organic complex formers on the mobility.

The main results were:

- the chemical composition of the sediment pore water seemed to be, in the upper layers, strongly related to the chemical composition in the lake water, The ionic strength varied with depth.
- chemical processes of large importance are sorption of radionuclides on suspended material in the water, as well as migration and fixation in the sediment.

5.8.3 Transport study of nuclides in sediments

The evaluation of radionuclide diffusion in sediments was studied [Andersson, 1987 and Andersson et al., 1992]. About 40 sediment cores that were doped in the middle with radionuclides (Tc-99, Sr-85, I-125, Cs-134, Eu-152, Th-232 and Am-241) were analysed in 1986, a year after repositioning the original lake sediments. Afterwards they were again repositioned and were taken up and analysed after the ice-cover of the lake had melted in spring 1987.

On subsequent occasions the cores were recollected and distribution of the nuclides within the core was recorded. The migration was correlated to the physical and chemical sediment properties.

The main conclusions were:

- the sorption of Sr, I, Cs, Eu and Am in the upper layer of the sediment was much higher than in the rest of the sediment. This may result in retardation at the surface,
- diffusivities are of the same order of magnitude as for e.g. bentonite clay and deep sea sediments,
- the mobility of Tc and Np are low due to the low redox potential in the sediment.

5.8.4 Modelling of dose variations due to changes in the recipient

The field sampling and laboratory study phase were finished in 1986, and a third phase included modelling of how the growth and changes of the sediments might influence the behaviour of radionuclides released from a repository as well as prediction of the behaviour of “immobilised” radionuclides when the lake sediments would turn into an agriculture area. Dose calculations for some radionuclides were initiated and reported in [Sundblad et al., 1988].

As expected the transfer of activity from groundwater to man is strongly influenced by the primary recipient. Depending on the radionuclide, the transfer factor will change when a lake is formed, as the lake will get smaller by eutrophication, as the sediments are converted into agricultural land etc. Some nuclides, like cesium, show a maximum transfer factor when the lake can support a sustained fish population, others, like technetium and iodine, show a maximum transfer factor when producing cereals or when cattle graze at the shore sediments. For Pu-239 and Pa-231 the calculated exposure increased with about a factor of 80 during the drying up of the lake to the soil phase, while doses for other nuclides were much smaller, varying from 0.4 up to 8. This means that the dose for some nuclides even decreased.

5.9 Biosphere characterisation and natural radioactivity

Knowledge of concentrations and migration patterns of natural radioactive elements in the hydro- and biosphere of repository sites is valuable for:

- Estimation of the “background” dose level due to natural radioactivity.
- Calculation and estimation of “super-imposed” doses due to release of similar (Ra-226, U) or analogous elements to radionuclides from a repository.

5.9.1 Biosphere characterisation at geological sites

In parallel to the geological site investigation, a characterisation of the biosphere in general and of soil and surface waters with regard to natural radioactivity were made in four investigation areas; Fjällveden, Voxnan, Gideå and Kamlungekölen (see Figure 5-1). Besides general conditions in Finnsjön and Sternö (see Figure 5-1)were discussed [Sundblad & Bergström, 1983 and Evans et al., 1982].

The recipient areas were defined and their climate, hydrology, bedrock, soil, vegetation, land use and yield from arable land were described, as well as the yield of fish for the surface water of interest. The potential exposure pathways and model system at the different areas were defined.

Long-term variations of geology, climate, hydrology, land-use, acidification and evolution were described. The possible development of the recipient areas was also discussed.

5.9.2 Experiments at Klipperåsen and Bjulebo (1984 - 1988)

During 1985 two new biosphere characterising studies were completed, one at Bjulebo, the other at Klipperåsen, both situated in the south-east part of Sweden (see Figure 5-1), [Sundblad et al., 1985].

The two recipient areas are completely different. In Bjulebo two types of entrance points of the radionuclides were identified: a brackish bay and a lake. Klipperåsen, on the other hand, is an inland site where bogs are frequent. One of these is a former lake situated above a marked fracture zone in the bedrock.

A complete geological site investigation was performed in Klipperåsen. This was also intended for Bjulebo, but a new law reserved this region for recreational purposes, and therefore no drillings were made. Since Bjulebo is a typical Swedish coastal area, however, the surface investigations were completed.

Gamma ray surveys, covering representative soil types, gave average exposure rate values of about 18 μR/h for both sites. This corresponds to a radiation dose of about 1.5 mSv/year.

Concentrations of Th and U were determined in rock, soil and plant samples, and concentrations of Ra-226, Ra-228, Th-228, Cs-137 and K-40 in soil and plant samples. Average concentrations in Klipperåsen samples were for granite (dominating rock) 20.7 ppm thorium and 6.6 ppm uranium, for soil (upper zone), 5.6 ppm thorium and 2.9 ppm uranium and for peat 1.8 ppm thorium and 2.4 ppm uranium (dry weight). Fairly high concentrations of the elements were observed in some organic soil samples, 11.5 ppm thorium and 13.1 ppm uranium. The nuclides in the uranium and thorium decay chains were usually not in equilibrium, indicating different migration patterns for the radium, uranium and thorium isotopes. A much higher root uptake of radium isotopes compared to uranium and thorium isotopes was observed.

The water quality and the content of uranium, Ra-226 and Rn-222 in ground- and surface water samples were also determined. The Ra-226/U-238 activity ratio was in average 0.1 for the Bjulebo and 3.1 for the Klipperåsen water samples, i.e. the uranium content was roughly the same, whereas the Ra-226 content was very low in the Bjulebo water samples.

However, among these results fairly high levels of some nuclides were observed in certain organic soils and peat samples. As the origin of these nuclides could not be clearly explained, new samples were taken and analysed and the possible mechanisms to the build up of high concentrations were discussed in Landström & Sundblad [1986]. The leaching of uranium and thorium from the alluvial zone of a podsolic profile and the enrichment in a nearby peatlike horizon was demonstrated. In peat bogs, the reason for the high levels of uranium and thorium and Cs-137 (bomb test fallout) were more complicated to explain. The Ra-228/Th-232 disequilibrium and the presence of Cs-137 were strong indications of current or recent migration, and indirectly of groundwater flows in the peat bog. Part of the cesium seems to have entered the bog via groundwater from below, and part of it from the surface, migrating downwards. A fractionation of Ra-226 and Ra-228 by the plant nutrient cycle was also observed.

5.10 Chernobyl fallout investigations (1986 - 1994)

In April 26 1986 at 01.26, the reactor accident in Chernobyl caused a substantial release of radionuclides into the atmosphere. After a long travel, some of these deposited as fallout in Sweden. This provided opportunities to study the turnover of e.g. Cs-137 in ecosystems.

5.10.1 Initial measurements (1986)

Because two of SKB's geological study-sites, Gideå and Finnsjön, were quite close to areas that obtained the highest fallout of radionuclides in Sweden, see Figure 5-3 – 5-5, a field sampling programme was initiated. The study was performed as a co-operative research between Studsvik AB, Nyköping, Chalmers University of Technology, Gothenburg, and Geosigma AB, Uppsala.

In addition to Gideå and Finnsjön, surface contamination was measured at six other places: Trödje, Brunne, N. Tannflo, Örnsköldsvik, Gäddede and Stöcksjö (see Figure 5-5), the last one of which was covered with snow at the deposition occasion. The results from these measurements [Gustafsson et al., 1987] are shown in Figure 5-6.

An initial compilation of the results from the sampling during summer, autumn and winter 1986 was ready in the middle of 1987 and published in Gustafsson et al. [1987]. The possibilities of using that material for validation of nuclide migration models in the biosphere or in the groundwater were evaluated and formed a basis for future efforts.

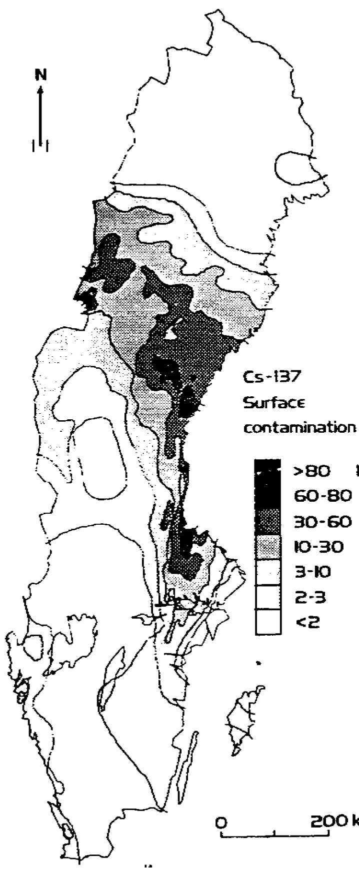


Figure 5-3 Deposition of Cs-137 computed from air surveys using 2-4 NaI detectors with a volume of 4.2 litres. The map is based on data from measurements performed between May and October 1986 by the Geological Survey of Sweden on commission by the Swedish Radiation Protection Institute.

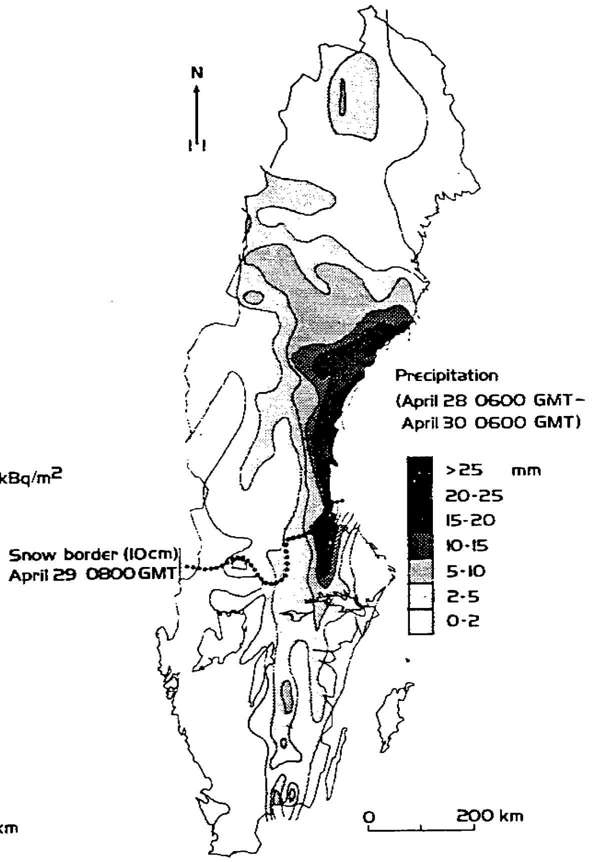


Figure 5-4 Measured precipitation (mm) over Sweden during April 28 at 06.00 to April 30 at 06.00, Swedish daylight saving time. (Data from Persson et al., 1986). North of the snow border, Sweden was covered by more than 10 cm snow on April 29 at 0800 GMT.

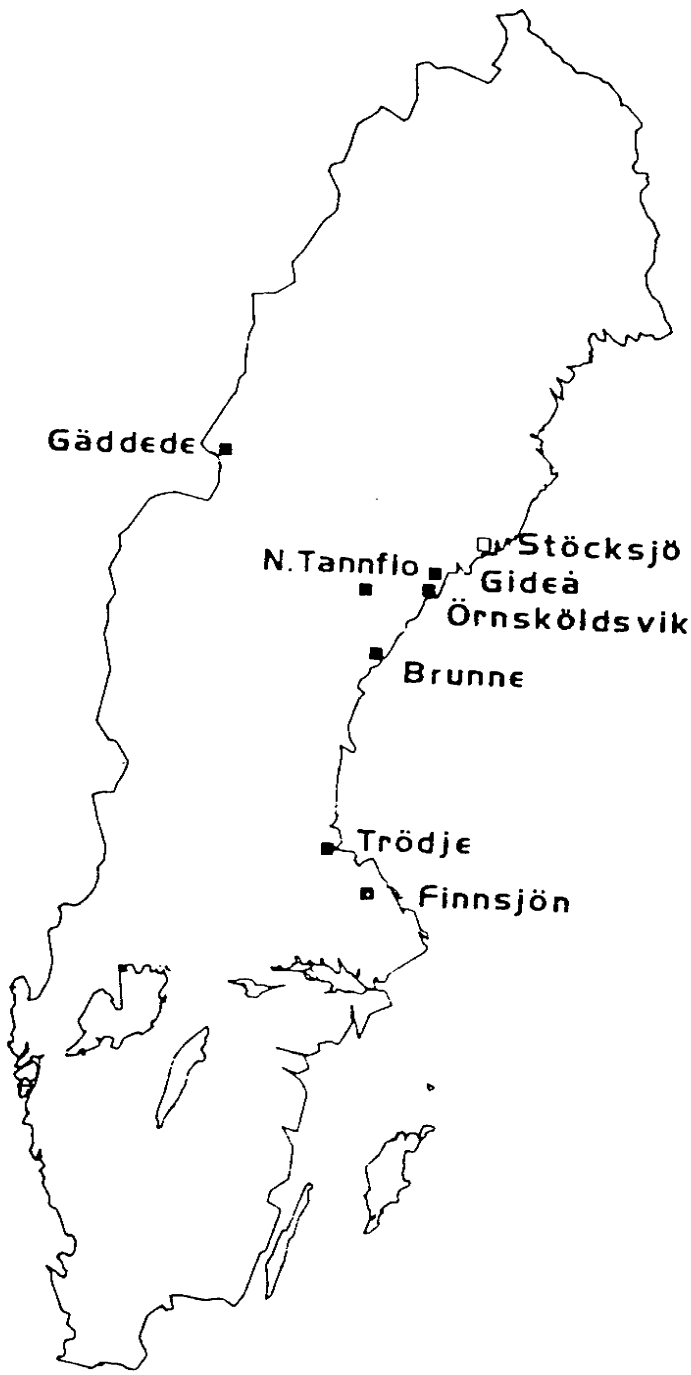


Figure 5-5 *Location of the study sites for surface contamination after the Chernobyl accident. The open square marks the location for snow sampling at Stöcksjö.*

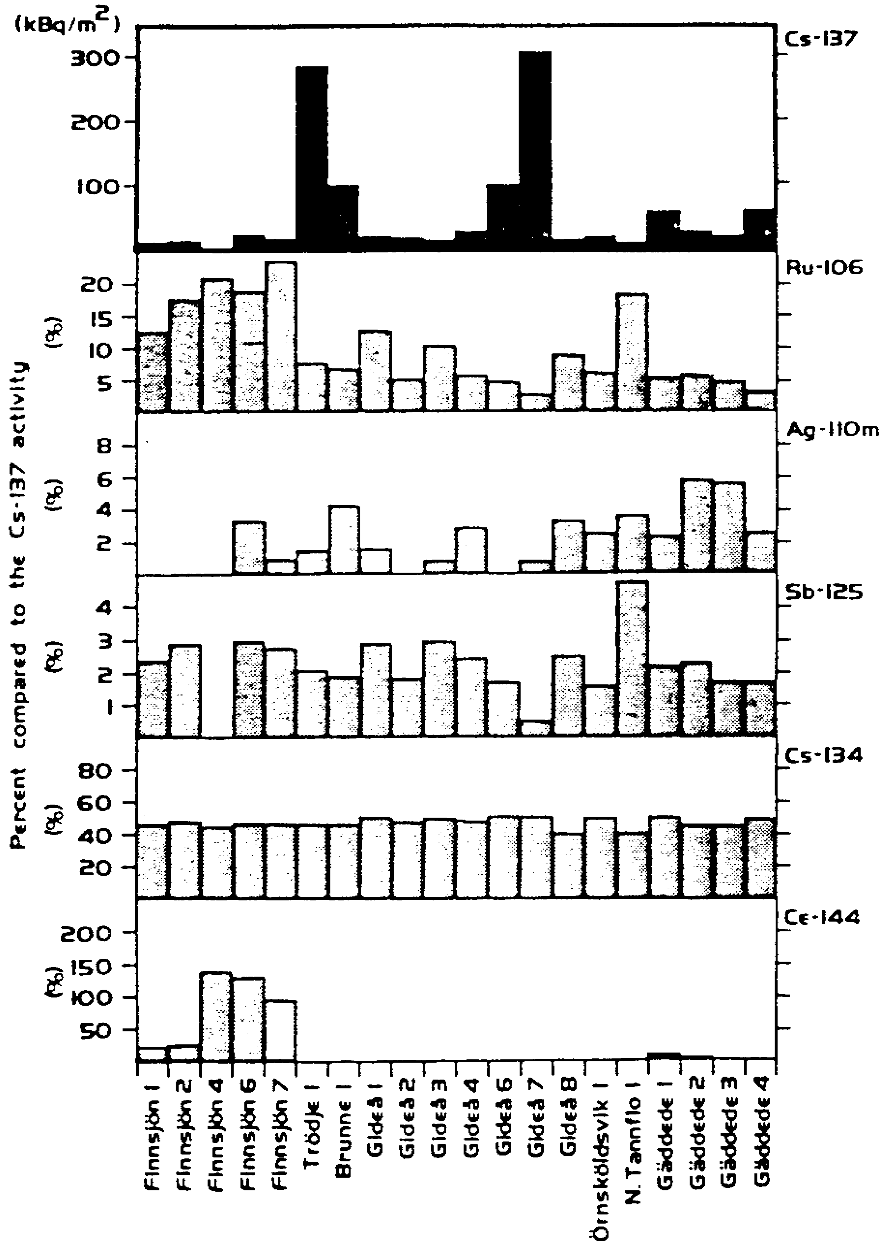


Figure 5-6 *The Cs-137 surface activity and the relative percentage occurrence of Ru-106, Ag-110m, Sb-125, Cs-134 and Ce-144 compared to Cs-137. All radioactivities were decay corrected to April 26, 1986.*

5.10.2 Further studies at Gideå and Finnsjön (1987 - 1994)

During 1987 and the following years, the extensive sampling of the radioactive fallout from Chernobyl in Gideå and Finnsjön continued. The aim was to study the initial deposition and its subsequent redistribution in soils, sediments, vegetation, surface and groundwater [Carbol & Skålberg, 1989 and Ittner, 1990].

The possibilities to use the material for validation of nuclide migration models in the biosphere and in the groundwater were shown to be good. SKB continued the sampling and initiated an evaluation effort later on [Carbol et al., 1988, Liljenzin et al., 1987, Ittner & Gustafsson, 1989, Sundblad & Mathiasson, 1990, Ittner et al., 1990, 1991a, Sundblad & Mathiasson, 1991 and Mathiasson & Sundblad, 1992]. These results were then used for validation of nuclide migration models in the groundwater and the upper soil layer. Model evaluations were performed using both compartment models [Sundblad & Mathiasson, 1991 and Sundblad & Mathiasson, 1994b] and continuous flow models [Ittner, 1992]. To get a better understanding of the total flows, a soil map was prepared for the area [Ittner et al., 1991b].

Another main issue was the chemical properties of the observed radionuclides, studied by migration in soil [Carbol & Skålberg, 1989, Ittner et al., 1990, Berg, 1991, Ittner et al., 1992, Carbol, 1993 and Carbol et al., 1994]. Measurements of radionuclides in samples of deep and superficial groundwater, soil profiles and well sediment from the Gideå and Finnsjön areas were therefore performed. The studies initially included many radionuclides but later a concentration on the long-lived radionuclides Co-60, Ag-110m, Ru-106, Sb-125, Cs-134 and Cs-137 [Mathiasson & Sundblad, 1992] occurred. As expected, there was a strong correlation between groundwater fluctuations and precipitation and temperature fluctuations at different periods during the year.

Exposure rate measurements along predefined profiles and gamma spectrometric measurements of soil samples were made in the Gideå area. Radionuclides at the hot spots identified at previous measurements had continued to migrate slightly [Mathiasson, 1994].

Measurements of the chemical composition of groundwater from a deep core -hole in the Gideå area were performed during three years.

5.10.3 Results

A summarising conclusion drawn from the study of the transport of radionuclides in soil was that the migration of radionuclides in till was relatively slow compared to the transport in sand and peat. Other conclusions from this study were that

- Co-60 moved relatively fast with 50 % of the activity found in the upper 5 cm of sand and till.
- Ru-106 seemed to move very fast and 50 % of the activity was found in the upper 7 cm in sand.
- Ag-110m had moved very moderately but it was observed that this nuclide was difficult to measure because of the low activity.
- Sb-125 seemed to move very fast with 50 % of the activity found in the upper 7 cm in till.
- Cs-134/137 could be found with 50 % of the activity in the upper 3 cm in sand and till.

Measurements of radionuclide content in sediment profile samples taken in a shallow well indicated a very fast migration through the sediment, shown by an almost straight radionuclide concentration profile versus depth.

The measurements in the deep drill hole in Gideå indicated an activity pulse of long-lived radionuclides, present in the Chernobyl fallout, at all sections (28-96 m, 97-106 m and 107- m), which was surprising since the water flow at these depths is very low (approximately 0.05 l/min). The Ru-106 peak arrived 263 days after the fallout to the 96-107 m level, while the peak of Co-60 and Cs-137 arrived at 599 and 516 days, respectively [Ittner et al., 1990]. This transport speed, discussed in Ittner et al. [1991a] was surprising as some previous experiments [Abelin et al., 1985] had showed that cesium is strongly sorbed. Other experiments have shown a minor amount migrating almost without any retention [Landström et al., 1983]. A possible explanation can be the speciation or the existence of organic complex or colloids or particles. The speciation analyses showed that cesium is not transported in the cationic Cs^+ form, as it is found in the anion exchanger or charcoal in the deep groundwater. In the surface water, on the other hand, it is transported as a cation [Carbol, 1993].

The modelling results served as a quality control on the measurements and indicated, among other things, that only 5 % of the initially deposited Cs-137 had left the area after five years [Mathiasson, 1994]. A model validation was performed and it was shown that it is possible to predict the turnover of Cs-137 in the biosphere as well as in the geosphere within relatively accurate ranges [Sundblad & Mathiasson 1994b].

The results from the whole study were presented in a dissertation monograph [Carbol, 1993]. It was found that about 10 % of the amount of cesium, which had left the area, was transported as particulate and the rest as cations. After five years, the major portion of the cesium was still in the upper 5 cm of the soil and predominantly in the silt-clay fractions. Only ~15 % of the cesium was considered to be mobile.

The levels of radioactivity in 1993 were very low, making further analysis difficult. The instrumentation was thus removed during 1993 and activity constrained to theoretical analysis.

5.11 The effect of groundwater inflow on sediments (1987 - 1991)

All the release pathways of radionuclides to man assume that the deep groundwater will reach the biosphere either in a well or in a groundwater discharge area. Such areas are often located at low points in the landscape and frequently in lakes or streams. Should a substantial groundwater outflow occur in a lake it is probable that it will have an effect on the sedimentation rate of the local area, on the chemical composition of the sediments and on its biological activity. All these factors are important parameters for the transfer of radionuclides to man.

In order to elucidate what differences there are between sediments in inflow and non-inflow areas, an investigation was started in 1987 [Sundblad et al., 1991b]. During that year an inventory was made to find suitable places for the main study. Especially two lakes were identified as suitable for the study, Hillesjön and Långsjön (Figure 5-7).

For comparison, measurements were also performed in two springs at Täckhammar and Lilla Ullfjärden in Södermanland, see Figure 5-7.

The major constituents, some heavy metals (As, Cr, Co, Zn), the uranium content of both sediments and the pore water were measured. Samples were taken at different depths in areas affected by the inflow and "normal" sediments. In the solid phase, rare earth elements and thorium were also measured and grain size and organic fraction were determined.

No significant processes that required a different modelling were found, at least not with the fairly coarse methods that were used. The enrichment of uranium was shown to be correlated to the levels of organic matter. The immobility of Ti, Zr and Hf in aquatic solutions was confirmed in the study.

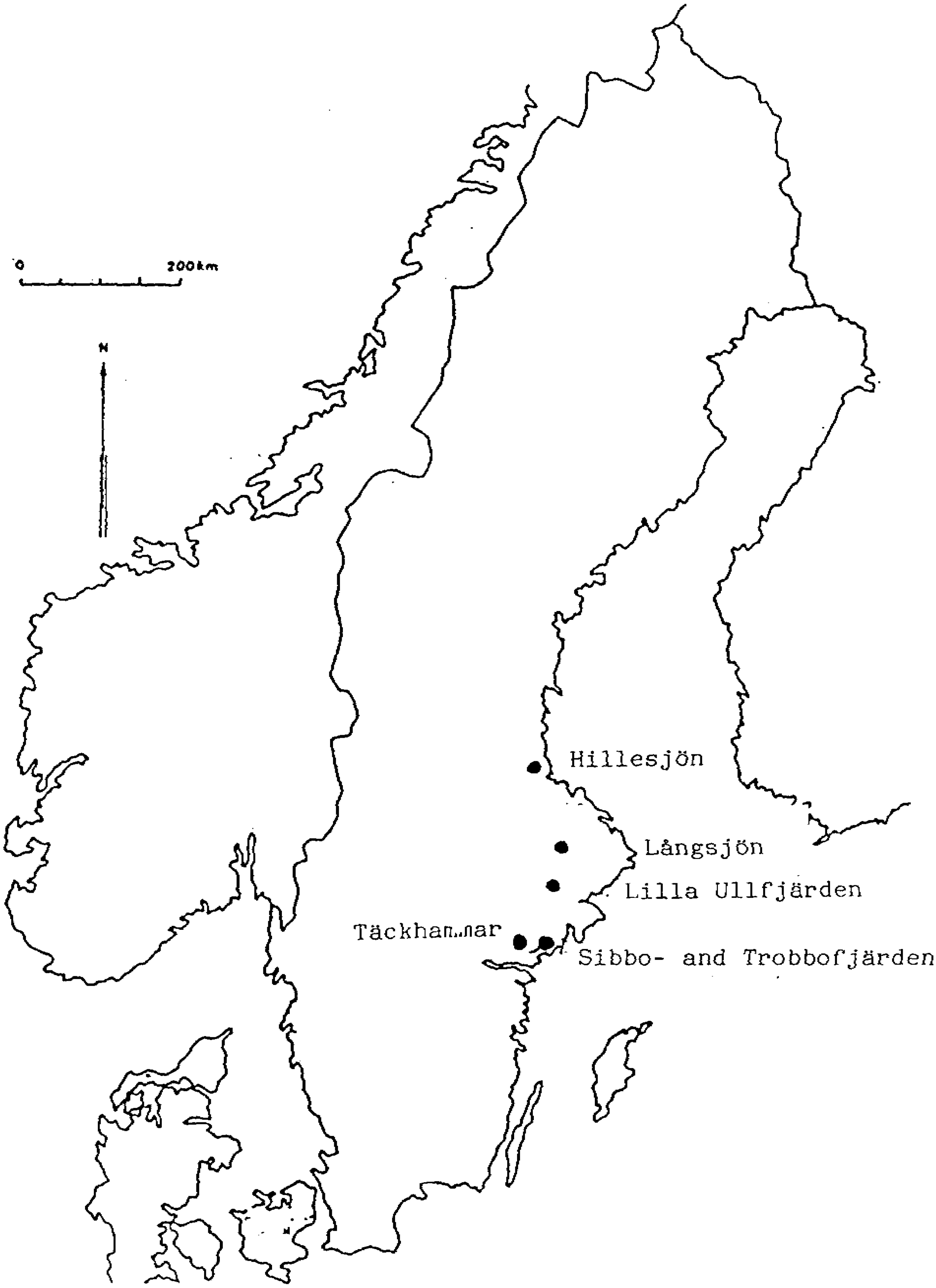


Figure 5-7 *Locations of investigated lakes.*

5.12 Site specific studies of recipients at Äspö (1989 - 1994)

Postglacial and glacial sediments and soils were studied in the archipelago around Äspö on the Swedish east coast (see Figure 5-1), with special interest in the influence of discharging groundwater. Äspö was selected because the site was carefully investigated due to the location of a deep rock laboratory.

This project was divided into three phases:

Phase I — Prestudy to find out what data are available, a preliminary field study and planning

Phase II — Recipient studies regarding surface and groundwater and water flows through the sounds, estuaries and coastal area

Phase III — Recipient evolution - modelling of likely evolution of the coastal region in the time perspective of 1 000 to 10 000 years.

It was assumed that by analysing the mineral composition and natural radiation in sediments and soil samples at the site, it would be possible to draw some conclusions about the history of long term radionuclide transport. Comparisons with modelling of future situations, when the flow patterns may have changed, could also be valuable.

5.12.1 Measurements

Sediment samples (0.5-6 m sediment depth) from the water around Äspö were taken at 22 sites [Sundblad et al., 1991a]. 15 sites were concentrated to the area SE of Äspö. Soil samples (0.4-2 m depth) from four sites on Äspö were characterised, and in some cases neutron activation analysis was performed.

The chemical composition (about 30 elements, including Na, Cs, Rb, Cl, Br, Fe, Th, U and rare earth elements) of soil and sediment samples was investigated. The concentration of F, Br, Cl, SO_4 and NO_3 were analysed in interstitial water from selected clay samples. The results indicate that the water exchange between the sediment layers generally is limited.

Some anomalies concerning Cs, Rb, Cl and Br, indicated that the rising groundwater influenced the sediments. The composition of the groundwater (types of ground- and marine water) was addressed by factorial analyses. Samples from above the fracture zone contained a pore water with some Baltic water, mixed either with surface groundwater or with older more saline water [Sundblad, 1992]. This was consistent with the very variable and complicated flow pattern which was assumed in the fracture zone [Smellie & Laaksoharju, 1991, 1992 and Wikberg et al., 1991].

Phase II was initiated in 1991 and continued during 1992. The flow patterns in surrounding bays were recorded for use in coastal zone models [Sundblad & Mathiasson, 1994a].

The chemical composition of sediments from the Äspö area was also investigated [Landström et al., 1994]. As much as 90-99% of the original content of Na, Cl, and Br in the pore-water had been leached, probably by percolating surface water. The large amount of leached ions may have contributed to the salinity of the underlying bedrock according to the authors.

The stratigraphy and element concentrations reflected changing sedimentation and weathering conditions. Of special interest was the presence of gravel zones between the clay layers as they may constitute important paths for element transport. They may be analogous to the moraine zone between the clay and the bedrock. This was further studied, and reported in [Aggeryd et al., 1999]. The gravel zones differed significantly from their surroundings with respect to the chemical composition of porewater. This is probably due to different conditions in the gravel zones regarding parameters such as pH and redox potentials, which may be explained by a different origin of porewater in the gravel zones compared with the surrounding sediment layers. The authors therefore suggested that these zones may act as important pathways for the transport of radionuclides from an underground repository to the biosphere.

In Landström et al. [1994] it is also pointed out that earlier deposited elements in the sediments may either be further dispersed by wave actions or if sediments are transformed to soil by land-rise the changed chemical conditions may mobilise the elements.

The results from these studies were also included in a large study of the performance of the geological barrier to protect a repository from dissolved oxygen entering vertical fracture zones from the surface, especially during construction and operation of the repository [Bannwart, 1995]. The study was called REDOX.

5.12.2 Modelling

A primary model approach was set up [Sundblad & Mathiasson, 1994b]. This model aimed to estimate the radionuclide transport from a deep repository located on the coast at a site like Äspö.

5.12.3 Dose factors in the Äspö area

An attempt to estimate site specific dose factors to the local population of the Äspö area was performed for seven nuclides; C-14, Tc-99, I-129, Cs-135, Np-237, Pu-240 and Am-241 [Nordlinder et al., 1994]. An area of approximately 100 km^2, around Äspö, was studied and six types of recipients were identified. Using identified pathways at the site and current people's habits, a set of "dose factors" with ranges of uncertainty were calculated. According to the results the highest doses would be via water from wells and cultivation of peat-bog soil.

A re-evaluation of these data was done with the assumption that the released radionuclides enter the biosphere via a major crush zone, thereby distributing the release to different recipients [Nordlinder, 1996]. In this study the highest doses were reached via consumption of fish from a pond with groundwater inflow as well as after intake of food grown on peat soil after long time accumulation of nuclides. The results of the studies may be used in future safety analyses for a hypothetical deep repository located in the area.

5.13 NATAN (NATural ANalogues)

One way of understanding long time transport processes in the biosphere is to study transport of naturally occurring elements. Sorption and migration of radionuclides in the interface between biosphere and geosphere is of special interest. In a prestudy seven candidate sites was investigated with respect to their suitability [Aggeryd et al., 1994].

A peat bog and its recipient at Äspö was selected for a natural analogue study [Aggeryd et al., 1995]. The element composition in the bog and in the runoff surface water, as well as the weathering of elements from the surrounding bedrock were analysed. Mass balance calculations showed that two completely different trends of transfer of elements into and out of the peat bog occur. Elements like Ca, Mg, Na and Sr are transferred to the groundwater whereas Cs, Rb, Th, U and rare earth elements are reversally transferred from the groundwater to the bog where accumulation takes place.

Another conclusion drawn from the study was that natural analogue studies are useful tools for validation and improvements of biosphere models despite the difficulties in finding isolated systems and well defined source terms.

5.14 Conclusions from experimental results and gathering of environmental data

Several experiments and field studies were performed in order to obtain more data about biospheric processes, and to characterise the biosphere at selected places in Sweden. The possible development of the biosphere under the very long time spans considered in safety studies was also treated. The data and methods may be useful in both further safety studies, and in making biospheric studies at sites that will be proposed for site investigations.

6 Model development

Development of models has been a continuous process throughout the biospheric research programme. Models for several technical designs, scenarios and typical locations have been constructed. Experience from earlier work has been used to improve modelling in later projects. Verification and validation efforts have been performed to increase precision and reliability of the model results, in order to be able to make reasonable illustrations of doses in the case of failure of the technical barriers for a repository for spent fuel. as well as for a repository for low and intermediate level waste.

6.1 The distribution of radionuclides in soils and sediments (1989)

Modelling of transport of radionuclides in soils and sediments have been heavily relying on the sorption assumption expressed as a single K_d-value. There was, however, a need for techniques to model this important part of the biosphere models in a better way [Kelmers et al., 1987 and Elert & Argärde, 1985]. A project was therefore initiated in 1989 to be able to better understand the long-term modelling of accumulation of nuclides in sediments and soils. This can be achieved by:

- Extending the understanding of sorption phenomena relevant to both the biosphere and the geosphere

- Using thermodynamic data and sorption data to explain and, hopefully, reduce uncertainty within the biosphere modelling (as the large intervals of uncertainty today mostly are due to the highly variable K_d- values found in the literature).

The study was first expected to be reported in 1990, but had to be extended since some main difficulties ensued, namely:

- Organic substances would not fit into thermodynamics
- Redox fronts in organic matter was found to be important
- Biological processes as bioturbation showed necessary to be considered

To deepen the knowledge about the theoretical background to K_d-values, available theoretical models for ion-exchange and surface-complexation were adapted for biospheric conditions [Puigdomènech & Bergström, 1994]. A summary of the report was published in Nuclear Safety [Puigdomènech & Bergström, 1995].

The results showed that the work with surface complexation model for actinides increased the understanding of both laboratory measurements and studies of natural systems. The surface complexation model could estimate the dependence of K_d as a function of important chemical parameters.

The power of the surface complexation model is that equilibrium constants, obtained under controlled laboratory conditions on well determined minerals, can easily be used to estimate sorption under a much wider variety of conditions. K_d-value for Ra e.g. could be more precisely determined if the Ca concentration in the environment was known.

6.2 Validation of models

6.2.1 General

BIOMOVS (BIOspheric MOdel Validation Study) was an international study launched in 1985 by SSI, to test models designed to calculate environmental transfer and bioaccumulation of radionuclides and other trace substances. To SKB this presented an opportunity to test the widely utilised modelling tool BIOPATH and the uncertainty tool PRISM in several applications.

The primary objectives of BIOMOVS were threefold, namely:

- to test the accuracy of the predictions of environmental assessment models for selected contaminants and exposure scenarios
- to explain differences in model predictions due to structural deficiencies, invalid assumptions and/or differences in selected input data
- to recommend priorities for future research to improve the accuracy of model predictions

The study has provided an international forum for testing and critically evaluating models commonly used to predict the transfer of radionuclides through the biosphere. BIOMOVS was the first organisation devoted to model testing in the field of radioecology and to:

- Require that each model prediction be accompanied by a quantitative estimate of uncertainty, and evaluate the uncertainty procedures and results
- Test the use of models developed for radiological assessment purposes to predict the biosphere migration and accumulation of a non-radioactive trace element (mercury)
- Utilise world-wide data sets on Chernobyl fallout to evaluate model predictions through the process of a blind test

BIOMOVS utilised two different approaches to fulfil its objectives, namely:

Approach A in which scenarios were formulated based on suitable observational data and model predictions were compared against independent data sets;

observations were not available for the modellers until predictions had been submitted.

Approach B in which model predictions and related uncertainty estimates for specific test scenarios were compared and the differences explained.

BIOMOVS has revealed the potential that doses arising from build-up of radionuclides in soils and lake sediments may exceed in magnitude those arising from the introduction of equivalent amounts of radioactivity in streams and lakes used for drinking water [Smith, 1989]. It has focused attention on the problems arising when modelling transport across the geosphere and the biosphere interface, as well as the transport of radionuclides in groundwater to surface soils in discharge areas [Zeevaert, 1990 and Jones, 1990].

User judgement plays a significant role in determining the outcome of a model prediction because of decisions required to interpret the description of the scenario, derive relevant parameter values, and estimate uncertainty. Thus, similar models with similar data bases often produced different results when these models were used by different groups. This has highlighted the need for more than one independent modelling group to be involved with critical environmental assessment activities so that differences in predictions can be identified and resolved. In doing so, the quality of assessment results is enhanced and the reliability of the results is improved.

6.2.2 BIOMOVS I (1985 - 1990)

Within the international study BIOMOVS I, ACTIVI from the BIOPATH package in combination with the PRISM system were used in three different B scenarios - the B2 scenario “Irrigation with contaminated groundwater” [Grogan, 1989], the B3 scenario “Release of Ra-226 and Th-230 into a lake” [Bergström, 1988] and the B5 scenario “Long-term evolution of a contaminated lake” [Smith, 1989]. In addition, models were developed using the codes above for a blind testing of the turnover of Cs-137 in three lakes. All these studies were funded by the SSI. In all of these scenarios, the most relevant processes and sources of conceptual and parametric uncertainty were indicated. Additionally, a dose assessment, supported by SKB, was performed for illustrating important exposure pathways for a variety of radionuclides. The contribution to dose from unit releases of Co-60, Sr-90, Cs-137 and Pu-239 to the Swedish lake Trobbofjärden were calculated [Bergström & Nordlinder 1990a].

Below follows a list of the main conclusions derived from the BIOMOVS I study (BIOMOVS, 1993).

- In trying to assess and improve confidence in model predictions of biospheric transport of radioactive and other trace substances the participants were made aware of the potential for very large uncertainties to be associated with any given prediction and for large discrepancies to occur among predictions submitted by different modelling groups.

- Once model predictions were corrected for common mistakes in programming and data entry, analyses of the results of the individual test scenarios revealed that confidence in model predictions was highest for well studied radionuclides (I-131 and Cs-137) and pathways of biospheric transfer (e.g. forage-cow-milk-pathway). In these cases uncertainties were usually well within one order of magnitude. For releases of long-lived radionuclides into the far future, the uncertainties were generally much larger than one order of magnitude, indicating low confidence in model predictions for scenarios involving these conditions [Zeevaert, 1990 and Jones, 1990].

- The presence of large uncertainties for predictions of concentrations of specific radionuclides in specific environmental media may not necessarily cause a lack of confidence in the overall assessment of dose or risk to man. The importance of the contributions of those nuclides and pathways to the total dose to a group or population would have to be considered. The B8 scenario [Whicker, 1990 and Bergström & Nordlinder, 1990a] was expressly designed to explore this matter.

- Scenarios for model intercomparisons must be most carefully and completely described, otherwise discrepancies due to interpretations and the appropriate selection of model and parameters will dominate overall uncertainties.

- In general, model complexity increases a model's flexibility for dealing with a variety of assessment questions. However, if site specific data are unavailable to take advantage of this flexibility, generic or default values must be substituted and the increased complexity in model structure may not lead to more accurate predictions.

BIOMOVS forcefully demonstrated the shortcomings of our present capabilities for biosphere modelling [Jones, 1990]. Older models involving well studied pathways and relatively short-lived radionuclides (e.g. Cs-137 and I-131) needed improvement, but especially the results for newer models for the longer lived radionuclides and less well studied pathways showed high variability. The situation clearly demands a remedy as basic parameters and their ranges could differ by 3, 4 and 5 orders of magnitude between modellers, leading to, in the worst cases, little or no overlapping even of the uncertainty ranges in results. Ideally, any modelling group given a specific scenario should calculate levels of activity in any compartment that agrees within a factor of 2. BIOMOVS has shown that such a target is a long way off even for the older well studied pathways.

Nowhere is the effect of the user more pronounced than in the uncertainty analyses. BIOMOVS has shown that there are such wide difference in the way individual modellers go about assessing the uncertainties, that nothing useful can be said about model uncertainty and uncertainty estimation. BIOMOVS revealed this situation which could not have been gained from a study of the text books on the subject.

The following parameters were identified as the ones with the largest uncertainties:

(i) Adsorption coefficients for soils and long-lived radionuclides (e.g. Tc-99, Np-237, Scenario B2 [Grogan, 1989]).

(ii) Bioaccumulation factors for fish, particularly for radium and thorium (Scenario B3 [Bergström, 1988]).

(iii) Concentration ratios between plants and soils (Scenario B2 [Grogan, 1989]).

(iv) Interception factors for spray irrigation (Scenario B2 [Grogan, 1989]).

(v) Resuspension factors from soils and other surfaces (Scenario B2 [Grogan, 1989]).

(vi) Distribution of radionuclides between dust and soil particles (Scenario B5 [Smith, 1989]).

(vii) Assessment of effects of climatic and geomorphologic changes on calculated doses and improved ways to model them (Scenarios B2 [Bergström, 1988] and B5 [Smith, 1989]).

A strong recommendation based on the experiences in BIOMOVS I was that whenever assessments are required for basing decisions of acceptability of a practice, at least two, but preferably more, independent modelling groups should participate in the work. This will help to identify and correct errors and misinterpretations and reveal the extent to which different approaches affect the predictions. BIOMOVS I demonstrated also the need of a close link between model developers and specialists in various scientific disciplines.

6.2.3 BIOMOVS II (1991 - 1996)

In 1991 the second phase, BIOMOVS II, was initiated at a workshop in Vienna in October and was jointly managed by five organisations.

- The Atomic Energy Control Board of Canada (AECB)
- The Atomic Energy of Canada Limited Research (AECL)
- Centro de Investigaciones Energeticas, Medioambientales y Technologicas, Spain (CIEMAT)
- Empresa Nacional de Residuos Radioactivos SA, Spain (ENRESA)
- Swedish Radiation Protection Institute (SSI)

Similarly to BIOMOVS I, the objectives of BIOMOVS II were threefold, namely:

- To test the accuracy of the predictions for environmental assessment models for selected contaminants and exposure scenarios
- To explain differences in model predictions due to structural deficiencies, invalid assumptions and/or differences in selected input data
- To recommend priorities for future research to improve the accuracy of model predictions

Four themes were set up for BIOMOVS II:

1 Scenario development and model intercomparison.
   - Uranium mill tailings (model intercomparison)
   - Special radionuclides
     Accidental release of tritium
     Turnover of C-14 in a lake (blind test)
   - Complementary studies

2 Uncertainties and validation
   - Guidelines for uncertainty analysis
   - Evaluation of the effect of user interpretation on model uncertainties
   - Use of natural analogue data
   - Effects of model complexity on uncertainty
   - Use of data from lysimeter experiments to test models for upward migration of radionuclides in soil

3 Reference biosphere scenario for long time assessment

4 Additional themes (Use of post-Chernobyl data for model testing)
   - Wash-off scenario
   - Cooling pond scenario
   - Resuspension
   - Multiple pathway analysis

All of these studies set up initially were not fulfilled, e.g. the "Use of natural analogue data" was not completed due to minor interest from the participants. Nevertheless, 16 technical reports were produced, of which summarising papers for most items were published in a special issue of Journal of environmental radioactivity [Baxter, 1999]. Below follows some brief summaries of the tasks in which SKB participated.

A blind scenario was set up where modellers were asked to model the turnover of C-14 in a small Canadian Shield lake, to which C-14 had been added. This scenario was interesting as C-14 had been shown to be a dose dominant radionuclide when released to a lake in the Safety assessments performed for SFR [Bergström & Puigdomènech, 1987 and FSA, 1991]. A blind test means that no results are made available until the calculations are performed. Estimates of concentrations of C-14 in water, fish and sediments were requested. The four participating models gave acceptable results when compared to the observations if the calculated ranges of uncertainties were considered. These were, on the other hand, quite considerable [Bird et al., 1999]. There was however a tendency to underestimate the levels of C-14 in fish which led to the conclusion that the modelling of the turnover of carbon in lake ecosystems should be improved.

In the working group "Complementary studies" (complementary studies to the reference biosphere group) the emphasis was put on how various models were able to perform an assessment based on site specific conditions and a well described data set. Some of these data were given as statistical distributions. The well-defined data set was selected in order to allow detailed descriptions of FEPs (features, events and processes). The analysis of the model results from concentrations of some selected radionuclides up to total doses showed that though there was a consensus about which FEPs to be used, the implementation of them varied among the participants. The agreement was best for transport of radionuclides in solution. Transport of radionuclides in solid form was modelled in many different ways although the results were the same. In similarity to the findings from BIOMOVS 1 the modelling of irrigation was identified as an area which needed improvements. It was also pointed out that mass balances should be considered to avoid modelling of impossible physical situations. Other outcome from the study was the need to improve generic and site specific data bases.

In the group addressing the “Evaluation of the effect of user interpretation on model uncertainties” three food chain models of varying complexibility were run for some selected scenarios by ten participants. Not all participants calculated results for all models and scenarios. Though all participants used the same codes, the differences in results were large; the total uncertainty was greater than the results from any single user. The reasons for discrepancies were the choice of parameter values and interpretation of the scenarios. In some cases “good” final results were a result of compensation of several errors earlier in the modelling process. As cited in Kirchner et al. [1999] “Although the effect of users’ assumptions on predictions was expected to be high, the extreme variability from ten users with one model came as a surprise. It is all the more alarming since the models for all scenarios were very simple with linear transfer between just three compartments, and participants had experience in this sort of modelling. More disparate results could be expected when using a more complex model.” In similarity to the recommendation from BIOMOVS 1 this group also pointed out the need for several groups to be involved in important assessments.

The “Reference biosphere group” addressed differences in biosphere modelling for waste repositories as such assessments include specific aspects such as releases in a distant future at which the human behaviour is difficult to predict. As cited from van Dorp et al. [1999] the group” has developed (a) a recommended methodology for biosphere model development, (b) a structured list of features, events and processes (FEPs) which the model should describe, and (c) an illustrative example of the recommended methodology. The Working Group has successfully tested the Interaction Matrix (or Rock Engineering Systems, RES) approach for developing conceptual models. The BIOMOVS II Working Groups on Reference Biospheres and Complementary Studies have laid the basis for considerable harmonisation in approaches to biosphere modelling of long term radionuclide releases.”

Some overall and general conclusions from the study can be briefly summarised as follows:

- Care must be taken when using results from models for decision-making, especially regarding long-term scenarios.
- Models are on the other hand useful tools. It is important to have collaborative multidisciplinary efforts when developing models.
- The need of blind testing is obvious for the evaluation of a model's validity.
- Complex models do not necessarily produce more accurate results.

- Uncertainties regarded so far are those attributed to parameter uncertainty but not to conceptual uncertainties.

Model work should not be carried out in isolation.

6.2.4 VAMP (1991 - 1994)

In the aquatic group within the IAEA/CEC program VAMP "Validation of Models on the transfer of Radionuclides in Terrestrial, Urban and Aquatic Environment and Acquisition of Data for the Purpose" [IAEA, 1989 and IAEA 1992b]. results and uncertainty analysis of modelling of Cs-137 in lakes were compared between working groups from several countries [IAEA, 1998].

The overall objectives of the VAMP programme were:

- to provide a mechanism for the validation of assessment models by using the environmental data on radionuclide transfer which have resulted from the Chernobyl release;
- to acquire data from affected countries for that purpose and
- to produce reports on the current status of environmental modelling and the improvement achieved as a result of post-Chernobyl validation efforts.

In the VAMP aquatic group several issues regarding the modelling of Cs-137 were addressed. The study included data for seven lakes of varying properties all over Europe. For a full description see IAEA [1998]. It was found that simple models with site-specific parameters gave satisfactory results for the studied five-year period [Nordlinder & Bergström, 1992].

All participants felt that the study had improved their possibilities to model the turnover of Cs-137 in lakes. The study analysed the observations as time series, showing sometimes large uncertainties coupled to the values. Good data are, as mentioned earlier, crucial for testing models. The definition "predictive power" was introduced and the study concluded that predictive models should be small but based on the most fundamental processes and model variables. The concept of "moderator" was also introduced for e.g. seasonal variability in runoff and water retention times. It is important to account for secondary load i.e. transport from land to water when predicting the long-term concentrations of Cs-137 in water. Interaction between water and sediments are important. It is also important to apply an ecosystem perspective when modelling cesium in lakes, considering fundamental lake properties, such as stratification, bottom dynamics and food web characteristics.

6.3 Verification of models

Verification applies to the accuracy in the numerical methods used for the modelling programs. It is a necessity to avoid programming mistakes. The solution methods applied in BIOPATH have been subject to several verifications [Forssén, 1977 and

Person & Nilsson, 1978]. Recently, both BIOPATH and PRISM were parts of one total model intercomparison called PSAC [Klos et al, 1993]. The verifications showed that the codes act satisfactory.

6.3.1 PSAC (1991 - 1993)

The international OECD/NEA exercise “Probabilistic Systems Assessment Code (PSAC) User Group of the OECD Nuclear Energy Agency” (PSACOIN level 1b) dealt with the verification of codes used in biospheric modelling and uncertainty analyses. Most of the work was done during 1991 and a report was published in 1993 [Klos et al., 1993].

The results showed good agreement among the seven codes applied. The major uncertainty in the results was due to the transport processes and not due to the modelling of exposure pathways. It was e g found that the parameters that were most critical for total uncertainty varied over time.

The vast number of transport processes involved could be rationally treated with compartment models where several processes were put together into one transfer rate.

6.4 Conclusions of model development

A knowledge base of model development has been achieved throughout the years of biospheric research. This regards conceptual modelling, as well as determination of suitable parameters and uncertainties. Codes have been improved continuously, and verified, and some models have been validated. By and large, the possibility to improve predictions of turnover of radionuclides in the biosphere, and resulting doses, has increased.

7 Effects on biota other than man

In the Radiation Protection Act from 1988 it is stated that man and nature should be protected against harmful effects of radiation. The need for consideration of protection of nature within the EIA (Environmental Impact Assessment) process has been pointed out by both SSI and SKI. The effects of radiation on plants and animals can be summarised as

- Change in species diversity or number of individuals
- Reduction of number of individuals of rare and threatened species
- Introduction of new species or prevention of normal re-growth
- Reduction of agriculture or otherwise productive areas
- Degradation of habitats of existing species

These effects are not likely to occur at acute doses below 0.1 Gy or dose rates below 1 mGy/d for animals and 10 mGy/d for plants [IAEA, 1992a].

A literature survey, reviewing studies which had attempted to assess whether or not effects at the population level will occur in plant and animal species at environmental radionuclide concentrations at which the radiological protection of man is ensured, was completed during 1993 [Jones, 1993]. The report also included an overview of the methods used in assessments of exposure to ionising radiation on populations of plants and animals. This report was followed by another [Jones, 1994] presenting data on radionuclide concentrations in biota in Scandinavia and summarising some projects which involved monitoring of radionuclide contents in soils, water, sediments and biota in Sweden. After that the topic has not been further investigated within the frame of SKB's biosphere research.

8 Computer codes

The computer codes developed during the biospheric research programme, and used for the safety analyses above, are briefly described in this chapter.

8.1 BIOPATH

The computer code BIOPATH is a general tool consisting of five Fortran subprograms, i.e. TRANS, MATRIX, ACTIVI, ACTRED and DOSBIO, which can be used for varying applications of compartment models that are based on first-order differential equations. The generic quality of the code systems allows a large number of compartments and their interconnections to be modelled. A variety of situations can therefore be adopted. The first time BIOPATH was used for assessment of doses to man from radioactive nuclides leaked from a final repository was in the KBS-1 safety analysis in 1977 [KBS-1, 1977].

As a consequence of the importance of the dose contribution from daughter products of the decay chains U-Th-Ra and Np-U-Th [KBS-2, 1978], the BIOPATH-code was further developed during 1979 - 1980 to facilitate calculations of doses from such decay chains [Bergström & Edlund, 1980].

Tools for calculation of the effects of environmental changes with time, e.g. the drying up of a lake and subsequent changes in the dietary habits of the population were also introduced in the code. The work was finished 1980 and reported in [Marklund et al., 1980 and Marklund, 1980].

The codes and processes are more deeply described in an assessment of model validity document [Bergström et al., 1995].

At present it is possible to include ten-nuclide, branching decay chains. The time variable reservoir sizes, however, have hitherto shown to be less useful, mainly due to lack of data and difficulties in predictions of the biosphere evolution.

Subroutines in the subprogram ACTIVI in BIOPATH are usually used for calculations on turnover of nuclides between compartments, while PRISM, see Section 8.2, is used as an overall tool for uncertainty estimates, using a specially user-defined subroutine for each application.

8.2 PRISM

Since the uncertainty and sensitivity analysis around 1980 became more and more important for the presentation of results in safety assessment calculations, a general tool, PRISM, for error propagation analyses was developed at Studsvik [Gardner et al., 1983]. The system makes it possible to use distributions of model parameters instead of single values. It consists of three subprograms; PRISM 1, PRISM 2 and PRISM 3. The Latin Hypercube sampling method is used for random generations of parameter values, each one selected within the given distribution for each parameter. This selection is carried out in PRISM 1. In PRISM 2 a user-defined subroutine describing the model is linked to all other routines contained in the basic program of PRISM 2 and performs the calculations corresponding to ACTIVI for all combinations of parameter values.

PRISM 3, finally, analyses the results. From this analysis it is possible to outline how the variation in values for each input parameter contributes to the variation in the final result values, one of which usually is the dose. In this way it is possible to select those parameters that have to be more accurately estimated, e.g. through experiments, in order to reduce the uncertainty. It is also possible to determine which processes that need further development because of their relative importance for the dose.

9 Summary and discussion

After the stipulation act was passed by the Swedish parliament an intensive work was addressed to find solutions for a safe disposal of spent nuclear fuel in order to get approval for operation of new reactors. Safety analyses were therefore carried out for a deep geological disposal of spent nuclear fuel to show that such management of the waste should be acceptable for the protection of humans. Thereby an intensive work of illustrating the consequences to humans from calculated releases of long-lived radionuclides to the biosphere started.

Already in 1977, when the first safety analysis was performed, a model called BIOPATH was developed see Section 8.1. This original model has during the years continuously been improved and a subprogram ACTIVI combined with an error propagation method, PRISM, is nowadays a general tool for solving first order differential equations, used in compartment modelling, see Section 8.2.

The first model used for KBS-1 simulated a gradual dispersion of radionuclides from the local zones over the regional and intermediate zones out to the global zone, thereby calculating individual as well as collective doses from multiple exposure pathways, see Section 2.1. The studies had an overall approach covering all biospheric compartments from which humans could be exposed from radionuclides. The model was based on a division of the biosphere into compartments which were assumed to be homogeneously well-mixed and similar in composition. Water and air were assumed to be carriers in the exchange of radionuclides between these compartments. Most of the rate constants used were obtained from observed redistribution of elements in the environments. The first study encompassed about 20 radionuclides, while nowadays the number has increased considerably. The number of exposure pathways have on the other hand decreased from originally 13 down to 10 because the experience has shown that the contributions to total dose from most external exposure pathways were insignificant. Initially, releases of radionuclides to a generic well, lake and coastal area were considered. It was early recognised that the model results were most sensitive to basic assumptions as well as how processes and data were implemented. The biospheres were considered to be quite generic and stationary according to the conditions of today, see Section 2.3. This latter assumption raised criticism of the results as the calculations covered millions of years during which the biosphere conditions may drastically change. It was unfortunately not clearly addressed that the calculations should be seen more as illustrations of future potential releases superimposed on the conditions of today during the time periods studied.

It was also early recognised that doses from releases of radionuclides to a well were inversely proportional to the water volume. The volumes used in the first study KBS-1 were based on estimates of infiltration waters from a drainage area leading to rather large volumes. This concept was used in all KBS-studies while the calculated conversion factors between exposures from unit releases of radionuclides applied in SKB-91 used the annual demands of water for humans and cattle to obtain the mixing volumes, see Chapter 4. This decreased the volumes considerable. On the other hand, in SKB-91 only a fraction of the radionuclides were assumed to reach a well. In the ongoing safety assessments SR 97 [SKB, 1999] observed water capacities for specific wells are used, leading to lower volumes than those used previously.

The safety assessments have so far mostly been considering generic biospheres, which is natural because the location of a repository for high-level waste is not yet known. However, the KBS-3 study, in contrast to KBS-1 and KBS-2, used data from various recipients from some potential sites for a location of a repository, see Section 2.3. The calculations performed for SKB-91 considered again generic biospheres.

KBS-1 to 3 as well as SKB–91 focused on wells, lakes and coastal areas as major recipients. Some rough estimates were however performed to investigate the consequences of releases directly to a peat bog. These screening calculations showed an increased dose when radionuclides directly entered peat bogs, see Section 2.3.

There has been a continuous development to describe processes more explicitly and implement element specific data in the models. Nevertheless the uptake of radionuclides in biota have always been described by help of steady state factors. However, several literature surveys have been made for selecting the most appropriate values to be used.

After the KBS-3 study a tool for studies of the importance for the results due to uncertainties and variations in parameter values was developed and this has since the middle of 80's been used when performing various assessments, see Section 8.2.

The dose assessments performed for KBS-3 were reviewed nationally as well as internationally. The main conclusion from these reviews was that generally the model used was sound, but more effort should be put on e.g. describing the effects of an evolutionary biosphere. There were of course also a lot of view points on specific parts in the modelling of which the reviewers were specialists, see Section 2.3.6.

The safety analysis for operational waste from nuclear power plants considered partly the biospheric evolution by looking at two main scenarios, one initially after closure when the bay Öregrundsgrepen was the recipient and one inland scenario as a consequence of the land rise, see Section 3.2. In the inland scenario the formed lake served as recipient of the radionuclides. This scenario was very similar to the one in KBS-3 but the lake volumes used differed between the two studies. The high contribution to doses from C-14 and a neglected transfer pathway in the global modelling lead to a deepened study of C-14, see Section 3.2.5. That study used a more sophisticated model for the turnover of C-14 in fresh-water systems, based on an intensive literature review. The collective dose commitment was about the same as the previous one, due to compensating factors. The individual doses were in good agreement to the earlier calculations.

Several literature surveys of biological uptake factors, such as root-uptake and distribution factors as well as distribution factors describing the fraction of an element in solid relative to soluble form have been performed both as separate studies or incorporated in the assessments. These focused on average values as well as identification of ranges to be adopted.

In parallel several field studies were carried out and some of the results from these have been used in the model developments, see Chapter 5. The studies also resulted in better data for use in the models. How all the field studies have been incorporated in the model developments is an interesting question. Without doubt the performed safety analyses pointed out important areas for improvements, such as process description and parameter values, which is after all the major constituents of the models. Therefore field studies of processes and transfer factors were initiated. These focused in general on naturally occurring radionuclides because these nuclides were at that time expected to be dominant from the dose point of view and they were also the ones possible to measure in the environment except for the bomb fallout of Cs-137 in the sixties. It was also early recognised that the inflow of radionuclides from the geosphere to the biosphere was a process which needed to be further studied.

These initial field studies encompassed exchange rates of radionuclides between soil/water as well as water/sediments. However, no erosion was included in the study, leading to extremely low transfer rates of the radionuclides from soil to water. The results were therefore not further used, see Sections 5.3 and 5.4.

The results from the other studies of naturally occurring radionuclides in water, peat bogs and vegetation have partly been taken into account when selecting parameter values for the assessments carried out. The studies relating to peat-bogs confirm the high sorption of uranium in peat, see Sections 5.12 and 5.13. However as peat bogs were very sparsely handled until the ongoing SR 97 study the results have not been used so much.

The studies of the evolution of a lake included an extensive data collection from lakes in various stages, see Section 5.8. It included mass balances and material turnover which showed that resuspension is a major source for gross sedimentation rates. The study with sediment cores spiked with radionuclides confirmed the low mobility of radionuclides located in the deeper sediments which was not affected by resuspension. The final model calculations showed that the doses from immobile radionuclides may increase with a factor of hundred when former sediments are transformed into soil.

The Gideå study was a co-operation work between Chalmers university, Geosigma and Studsvik EcoSafe, see Section 5.10. An intensive field program was carried out where the concentrations of radionuclides in horizontal and vertical profiles were measured during several years after the Chernobyl fall-out. This study lead among other things to a dissertation study of the migration of Chernobyl radionuclides in soil and waters and additionally increased the knowledge about the transfer of radionuclides in the natural environment. The results showed that the migration pattern varied among the radionuclides and the study paid also a lot of attention to chemical speciation. A major objective with the study was to obtain data for validation of models. A model test was performed with the use of 17 compartments to describe the area. One main problem is however that all the radionuclides were transferred from above while main entrance for radionuclides potentially leaking from a repository is from below.

Studies have also been performed for the entrance of elements in lake sediments from below, see Section 5.11. The outflow of elements in two closely located springs, of which one had an oxidising environment while the other was reducing, were also studied. The results confirmed the immobility of some elements and that uranium is strongly bound to organic matter. Nothing was found that lead to any changes in models.

The Äspö area is well investigated both as a potential site for a deep repository as well as for location of a deep rock laboratory. The site was therefore selected for studies of postglacial and glacial sediments as well as soils with special interest in the influence of discharging groundwater, see Section 5.12. The study aimed at obtaining knowledge about long term processes in the biosphere and obtaining values for making a prognosis over the area. The project was closely related to a geological study “The Redox experiment in block scale”. The data obtained for volumes and water retention times of the bays were used when studying site specific dose factors for the Äspö area.

The studies at Äspö continued as a NATAN-project, that is the use of natural analogues to study long-term processes in the biosphere, see Section 5.13. The element composition in a peat bog and in the runoff surface water, as well as the weathering of elements from the surrounding bedrock were analysed. Mass balance calculations showed that there is an exchange of elements between groundwater and the bog. A lot of data were collected and could probably be used for further studies with additional samplings.

Surface complexation models were developed in order to gain knowledge about the important adsorption of the elements to solid matter, see Section 6.1. The resulting distribution coefficients were in general lower than those found in the literature, probably due to that the organic material was not included.

The participation in the international model validation studies have been valuable check-points to follow the international development of models for the turnover of long-lived radionuclides in the biosphere, see Sections 6.2 and 6.3. The models used in assessments of SKB have been up to date with other models. The participation gave possibilities for intercomparison of model results and how various processes are considered and mathematically described. Additionally some blind tests were performed where model results were compared to independent data. Such testing showed e.g. that complex models were not always the most accurate. One major conclusion from the studies was that model developments is a multidisciplinary effort where modellers and experimentalists should co-operate closely. It was also pointed out that important assessments should be performed by at least two groups. The studies, especially the first (BIOMOVS I) strongly encouraged the need to make estimates of uncertainties coupled to the results. Such studies have however mostly been addressing the uncertainties coupled to parameter values while there is still a need to investigate the uncertainties coupled to conceptual parts of the models. Though international model studies are very valuable, care must also be taken when discussing harmonisation and equality of models. Too much consensus may lead to decreased innovations of model approaches and it is not always the majority which has the right opinion.

Literature surveys for effects on biota have also been performed and daa have been collected for radionuclide concentration in biota in Scandinavia, see Chapter 7.

The computer codes used in the modelling have continuously been developed and the results been mathematically verified, see Chapter 8. The first version could only handle a simple decay-chain and was quite rigid in its way of calculation of doses. Nowadays the code can handle up to ten decay products and is much more flexible.

A lot of interesting and valuable work has been performed during all the years. The importance of the geosphere/biosphere interface for the fate of radionuclides was early identified but is still an area for improvements.

In general few scientific papers have been produced. As also pointed out in the international model validation studies it is important to have a close co-operation between experimentalists (field studies) and modellers when designing conceptual models.

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