SKBF TEKNISK
KBS RAPPORT

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Radioactive waste management plan
PLAN 82

Part 1 General

Stockholm, June 1982

SVENSK KÄRNBRÄNSLEFÖRSÖRJNING AB / AVDELNING KBS

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RADIOACTIVE WASTE MANAGEMENT PLAN

PLAN 82

Part 1 General

June 1982

A list of other reports published in this series during 1982, is attached at the end of this report. Information on KBS technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26) and 1981 (TR 81-17) is available through SKBF/KBS.

FOREWORD

In Sweden, the primary responsibility for the safe handling and final disposal of radioactive waste from nuclear power production lies with the nuclear power producers. The waste management program is supervised by a special governmental authority.

The nuclear power utilities have delegated their obligations with respect to radioactive waste management to the Swedish Nuclear Fuel Supply Company (SKBF), owned jointly by them. The supervisory authority designated by the Government is the National Board for Spent Nuclear Fuel, NAK.

Swedish legislation requires the reactor owners (i.e. SKBF) to establish a program to ensure that:

1 The radioactive waste is handled and disposed of in a safe manner,
2 The reactors are decommissioned in a safe manner,
3 The necessary research and development is conducted to ensure compliance with 1 and 2.

The program shall contain an outline of all measures that may be necessary and shall specify in greater detail actions needed during a period of at least five years. An annually updated program shall be submitted to NAK for review.

Another requirement in the Swedish legislation is that the future cost of radioactive waste management shall be borne by the nuclear utilities that have produced the waste. A system of funds will be built up from special fees charged on every kWh produced by the nuclear power plants. The fee is set annually by the government on recommendation by NAK, and is based on, among other things, the program plan from SKBF mentioned above.

The criteria that determine the size of the fee are the estimated costs and the times at which various facilities and systems will be needed.

The present legislation entered into force in July, 1981, and the first of the annual plans was presented to NAK in June, 1982. The present report is an English translation of this plan (PLAN 82). The report is divided into two parts. Part 1 describes the present situation and existing plans for the research and development work and part 2 presents the costs and timetables for the necessary facilities and activities. Chapters 8 and 9 in part 1 present the timetables and cost estimates, respectively.

Swedish Nuclear Supply Co
August 1982

ABBREVIATIONS

BSAB	Encapsulation Station for Spent Fuel
BNFL	British Nuclear Fuel Limited
BSG	Encapsulation Station for Vitrified Waste
CLAB	Central Temporary Storage Facility for Spent Fuel
CLG	Central Temporary Storage Facility for Vitrified Waste
CLU	Central Temporary Storage Facility for Reprocessing waste, excluding Glass
COGEMA	Companie Générale des Matières Nucléaire (France)
CRIEPI	Central Research Institute of the Electric Power Industry (Japan)
FKA	Forsmark Power Group
HIP	Hot Isostatic Pressing
ICRP	International Commission on Radiological Protection
ISIRS	International Sorption Information Retrieval System
JSS	Japanese Swedish Swiss Cooperative Study of Radioactive Waste Glass
KBS	Handling and Final Storage of Nuclear Power Waste (Department within SKBF)
KBS-1	KBS' study on "Hauling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste," 1977
KBS-2	KBS' study on "Handling and Final Storage of Unreprocessed Spent Nuclear Fuel," 1978
NAGRA	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Switzerland)
NAK	National Board for Spent Nuclear Fuel (Sweden)
OKG	Oskarshamn Power Group
SFL	Final Repository for Long-lived Waste
SFR	Final Repository for Reactor Waste
SK	SYDKRAFT AB, Utility, owner of Barsebäck Power Plants
SKI	Swedish Nuclear Power Inspectorate
SSI	Swedish National Institute of Radiation Protection
SSPB	Swedish State Power Board
SKBF	Swedish Nuclear Fuel Supply Company

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1 BACKGROUND

1.1 INTRODUCTION

The measures needed in order to guarantee the safe disposal of radioactive waste products from nuclear power generation in Sweden are currently paid for and coordinated by the nuclear power industry via Svensk Kärnbränsleförsörjning AB (the Swedish Nuclear Fuel Supply Company), SKBF.

The activities conducted in Sweden within the field of waste management up to the beginning of the 1970s were essentially limited to the handling and local storage of reactor waste at the power stations. In 1973, these activities were broadened when the government appointed the AKA committee that was assigned the task of investigating the possibilities for a final disposal of the high-level waste obtained from nuclear power plants. The committee's terms of reference were later extended to include low- and medium-level wastes as well. The government National Council for Radioactive Waste (PRAV) was established in 1975 for the purpose of carrying the work of the AKA committee further. In response to the "Stipulation Act", SFS 1977:140, the nuclear power industry organized the KBS project at the end of 1976. The provisions and requirements of the Stipulation Act and the preparatory work that preceded it laid down the framework for the work conducted within the field of nuclear waste management in Sweden for the remainder of the 1970s.

Subsequently, the "Financing Act", SFS 1981:669, has given the nuclear power utilities a more formal and well-defined responsibility for nuclear waste.

This report is the first report presented by SKBF pursuant to the provisions of the Financing Act, which stipulates that the power utilities shall devise a plan for:

- research and development activities
- measures for the handling and final storage of spent fuel and the radioactive waste from it and
- the decommissioning of nuclear power plants.

According to the Act, "The plan shall include an overview of all the measures that may be necessary and shall describe in greater detail the measures that are planned to be adopted within a time span of at least 5 years". Moreover, it is stated that "The plan shall be reviewed annually".

According to the ordinance SFS 1981:671, the plan shall be submitted by no later than June every year to the National Board for Spent Nuclear Fuel, NAK. By no later than October each year, NAK shall submit the plan to the Government together with their own plan for:

- supplementary R & D activities
- an overview of measures for the monitoring and surveillance of the final repository
- supplementary measures for the handling and final storage of spent nuclear fuel and radioactive waste originating from it, as well as for the decommissioning of nuclear power stations.

1.2 LEGISLATION AND GOVERNMENT AUTHORITIES

Activities aimed at a safe disposal of radioactive waste from nuclear power generation are regulated by the following legislation in Sweden. Licences are normally issued by the Government. The processing of licence applications and the enforcement of regulations are handled by different govenment authorities.

The Nuclear Energy Act (1956:306) sets forth the fundamental stipulations for the erection and operation of nuclear facilities. The supervisory authority is the Swedish Nuclear Power Inspectorate (SKI).

The Radiation Protection Act (1958:110) contains regulations aimed at providing protection against ionizing radiation. The supervisory authority is the Swedish National Institute of Radiation Protection, SSI.

The Environment Protection Act (1969:387) contains regulations aimed at protecting the environment. The licencing authority is the National Swedish Environment Protection Board.

The Building Act (1947:385) §136a sets forth stipulations for the erection of so-called "polluting industrial plants". The Ministry of Housing processes cases and municipalities have the right of veto.

The Stipulation Act (1977:149) provides, among other things, that the owner of a new reactor must demonstrate how and where the high-level waste from reactor operation can be finally disposed of in a safe manner before the reactor may be charged with nuclear fuel. The Government makes the final decision on such matters after hearing from various selected advisory bodies.

The Financing Act (1981:669) stipulates that the primary technical and financial responsibility for the management and disposal of radioactive waste lies with the reactor owner and that the State shall oversee the arrangements and guarantee the financing of future activities by setting up funds to be financed by levies on power production. The supervisory and reviewing authority under the Government is the National Board for Spent Nuclear Fuel, NAK.

Nuclear energy legislation is currently under review and a proposal is expected to be presented during 1982. It is possible to distinguish three questions in the legislation:

- The first question - whether it is possible with present-day technology to achieve a safe final storage of high-level radioactive waste in Sweden - is dealt with by the Stipulation Act. This Act stipulates that the reactor owner must, prior to the charging of a new reactor with nuclear fuel, render an account to the Govenment of how and where high-level waste or spent fuel can be finally stored in a safe manner. In other words, the Act does not provide that an account must be given now as to how and where the final storage will take place. Nor does the Stipulation Act make any requirements with respect to the financial aspects of handling or final storage.

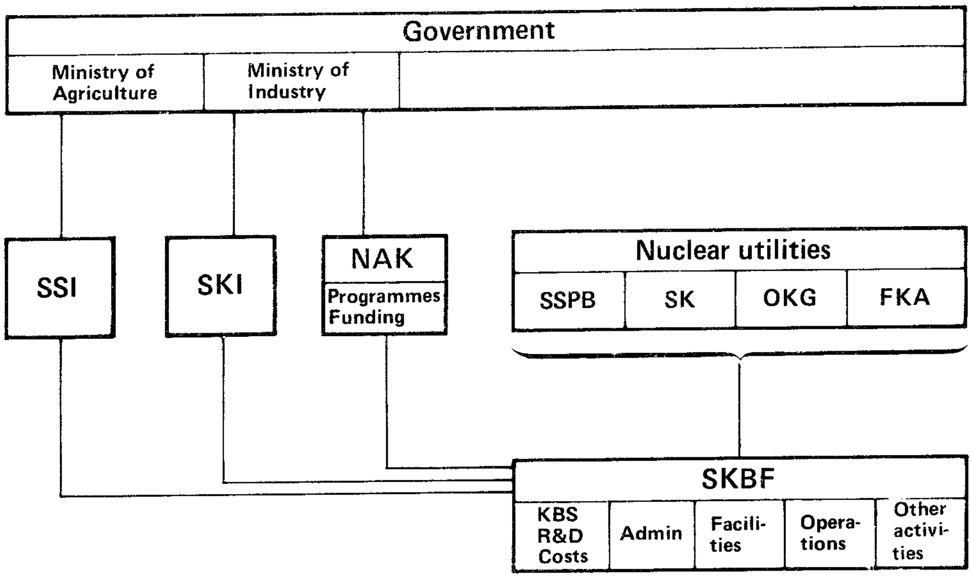
  The Stipulation Act came into force in 1977 and its provisions are only applicable to reactors that will be charged with nuclear fuel after the introduction of the Act. Consequently, the Act does not apply to reactors which became operational before the Act entered into effect.

- The second question concerns collecting basic data and making plans for how and when the various steps involved in the handling and final disposal of the radioactive waste and the decommissioning of the nuclear power plants are to be implemented and how the measures are to be financed. These activities are regulated by the Financing Act, which also provides for the setting-up of special government funds to ensure that undue financial burdens will not be imposed on future generations not having benefit from nuclear power production today. The Financing Act deals only with the handling of spent nuclear fuel and radioactive wastes deriving from it, and not the low- and medium-level wastes that are continuously produced in connection with the operation of the nuclear power plants. The nuclear power utilities will themselves set aside the funds necessary for the management of such wastes.

- The third question concerns the fact that the measures adopted for the handling of the wastes shall be implemented in such a manner that requirements on safety are met in an acceptable manner. Safety-related matters are regulated by the Nuclear Energy Act and the Radiation Protection Act.

1.3 ORGANIZATION, DIVISION OF RESPONSIBILITY AND OVERALL OBJECTIVES

Swedish activities in connection with nuclear waste management are organized by and large as shown in Figure 1-1.



Figur 1-1. Main features of the Swedish organization for the management of radioactive nuclear waste.

As envisaged in the drafting of the Financing Act, the Swedish nuclear power utilities have assigned to the jointly-owned company Svensk Kärnbränsleförsörjning AB (the Swedish Nuclear Fuel Supply Company), SKBF, the task of carrying out on their behalf the investigations and measures required to guarantee the safe management of radioactive waste from nuclear power generation. Matters pertaining to this are dealt with within SKBF in the following way:

1. The Department for the Handling and Final Storage of Nuclear Power Waste, KBS, is responsible for research and development work, preliminary planning of facilities and gathering of cost data.

2. The Administrative Department is responsible for the economic follow-up of reprocessing contracts and the computation of estimated future costs for waste facilities.

3. Special project groups are established in cooperation with SKBF's owners for the construction of facilities.

4. Before the facilities are commissioned, organizations for their operation are set up in cooperation with SKBF's owners.

All work is carried out in close collaboration with SKBF's owners, who are represented in a number of working groups.

For the execution of various assignments, SKBF engages the services of a large number of consultants and specialists. SKBF's own staff are primarily responsible for the initiation, planning and coordination of the work, the compilation and documentation of results and the practical application of the measures.

Within the realm of research and development, it is SKBF's intention to cover all areas that can be of importance for the choice of handling and storage methods, for the evaluation of the degree of safety they offer and for the procurement and operation of the necessary systems and facilities. As is pointed out in other sections of this report, it is not possible to conduct comprehensive activities within the entire field at the same time. Instead, it is necessary to adopt an order of priority. This, together with general flexibility in the planning work, is particularly necessary in view of the extensive international work being done in this field. Work that can be expected to yield results that should be taken into consideration in the ongoing Swedish programme. Up to now, high priority has been given to a) studies of the long-term function of final repositories and b) the engineering and procurement of facilities required at an early stage (CLAB, transportation system, SFR).

2 GENERAL PREMISES

2.1 THE SWEDISH NUCLEAR POWER PROGRAM

The Swedish nuclear power program currently comprises 12 reactors, of which 9 are in operation, 1 is in the process of being commissioned and 2 are under construction.

Table 2:1 Swedish reactors.

Reactors	Type	Output	Commercial operation
Oskarshamn 1	BWR	440 MW	1972
Oskarshamn 2	BWR	570 MW	1974
Oskarshamn 3	BWR	1050 MW	(1986)
Barsebäck 1	BWR	570 MW	1975
Barsebäck 2	BWR	570 MW	1977
Ringhals 1	BWR	760 MW	1976
Ringhals 2	PWR	820 MW	1975
Ringhals 3	PWR	900 MW	1981
Ringhals 4	PWR	900 MW	1983
Forsmark 1	BWR	900 MW	1980
Forsmark 2	BWR	900 MW	1981
Forsmark 3	BWR	1050 MW	(1985)

It is assumed here that no nuclear power reactors will be in operation after the year 2010 and that the reactors will subsequently be decommissioned. For the time being, the assumption has been made that decommissioning (including dismantlement) will commence approximately 5 years after shutdown and be completed by about 2025.

Of the reactors currently in operation, B2, R3 and F1 are licenced to operate until 1990, whereas the operating licences for R4 and F2 expire in 1986. All of these reactors have been charged with nuclear fuel after licencing under the terms of the Stipulation Act, and the time limits are linked to the fuel quantities provided for by existing reprocessing agreements.

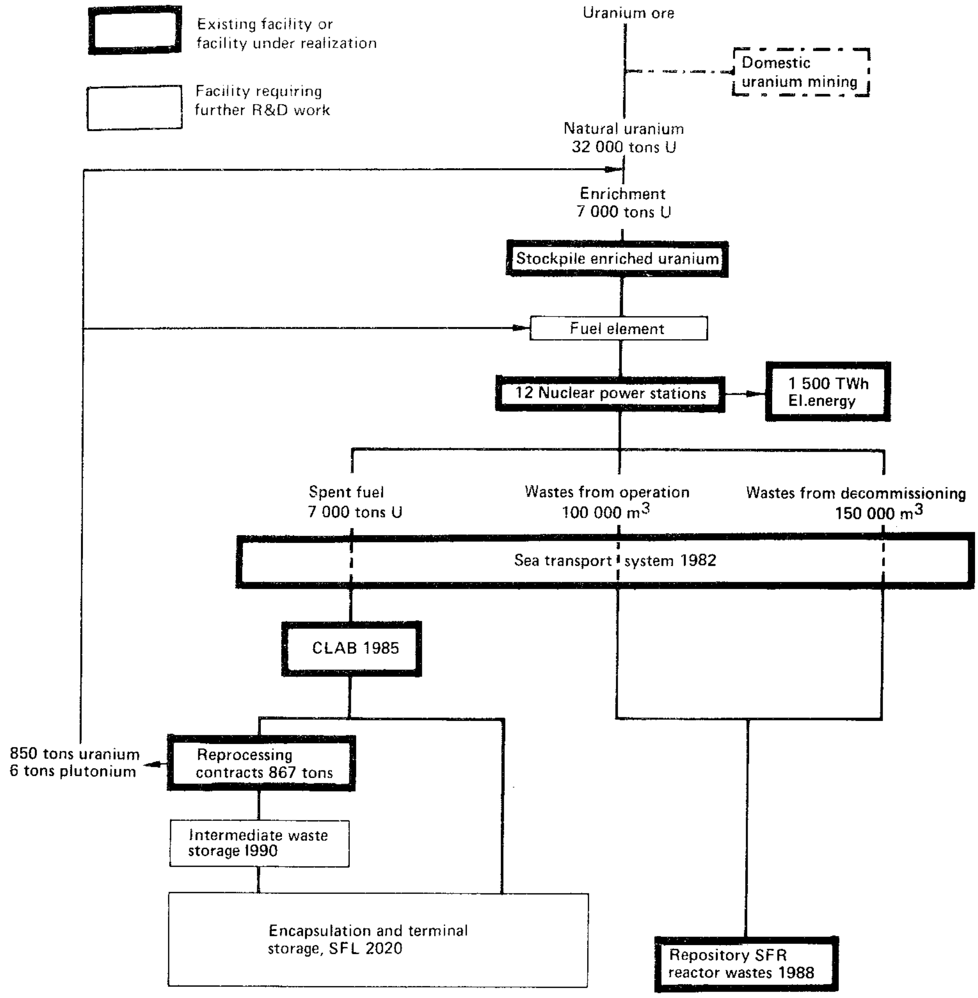


Figure 2-1. The Swedish nuclear power system.

A number of points in time can be derived from the reprocessing contracts which have been approved in accordance with the Stipulation Act. It is intended that the transportation of spent fuel to the reprocessing plant will commence in 1982. In addition to the separated uranium and plutonium, it is assumed that the wastes produced in the reprocessing process will be returned to the country of origin. This will take place in 1990 at the earliest.

A central storage facility (CLAB) for the intermediate storage of spent nuclear fuel is in the process of being erected at the Oskarshamn Power Station. The facility will become operational in 1985 with a storage capacity corresponding to 3 000 tonnes of uranium. A further expansion is planned during the 1990s. Reactors F3 and 03 are under construction and are planned to be taken into operation in 1985 and 1986, respectively. Licences are required under the Stipulation Act for fuelling. The applications will be based on an account of how and where an absolutely safe final storage of spent fuel without reprocessing can be made. These applications are planned to be submitted during the first half of 1983.

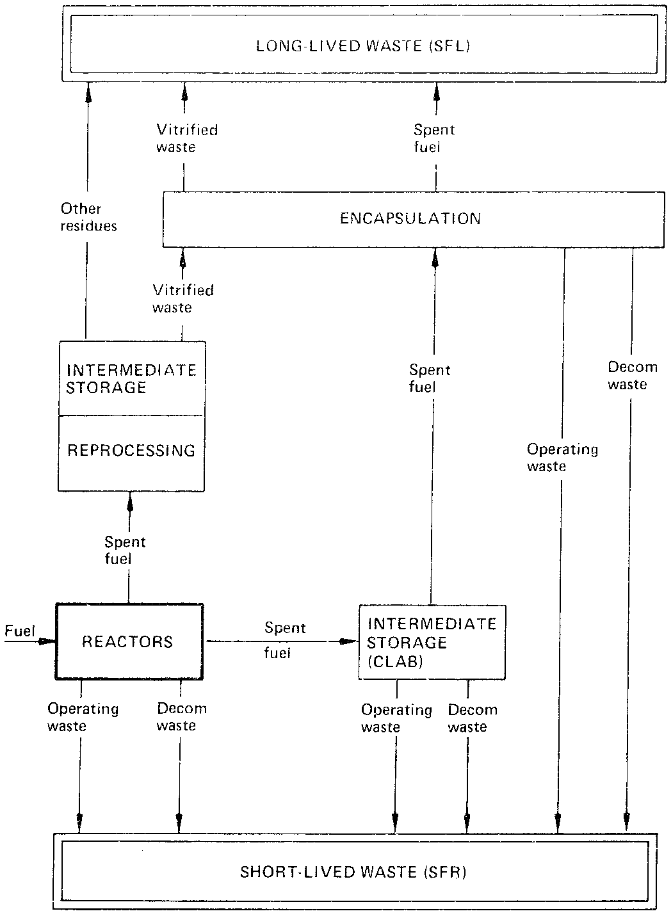


Figure 2-2. Handling of long- and short-lived wastes.

The low- and medium-level reactor wastes formed during reactor operation are currently being stored at the stations. A centrally-located final repository for reactor waste (SFR) is currently in the planning. A licence application has been submitted during 1982 for siting the SFR at the Forsmark Power Station. With construction starting in 1983, the facility is expected to be put into operation in 1988.

2.2 TYPES AND QUANTITIES OF WASTE

Radioactive wastes are generated in all stages of the nuclear fuel cycle - in uranium mining, fuel fabrication, reactor operation, reprocessing etc. This report deals with those wastes that originate from the operation and decommissioning of the reactors and from the various phases in the handling and disposal of the spent nuclear fuel, see Figure 2-1.

The wastes are normally subdivided according to degree of radioactivity into high-, medium- and low-level wastes. This categorization is primarily of interest from the viewpoint of handling, since it determines the radiation shielding requirements. From the viewpoint of final storage, a subdivision into long-lived and short-lived wastes is more appropriate, see Figure 2-2. The crucial factor in this context is how long it takes before the activity of the waste has declined to a harmless level. Long-lived waste is above all waste containing α emitting substances (transuranic elements). The borderline between short- and long-lived wastes is set for practical reasons at approximately 500 years.

Table 2:2 presents an overview of the different types of waste that are expected to have to be disposed of in Sweden. The quantities correspond to a total of 25 years of operation of each reactor in the Swedish nuclear power program, i.e. a total electrical production of 1 500 TWh. The volumes have been calculated on the assumption that the treatment methods that are currently used or planned to be used will be used in the future as well. It is further assumed that the quantity of fuel that is reprocessed will not exceed the amounts currently contracted for.

Future changes - for example as regards treatment methods, permitted releases etc. - can alter the values in Table 1. But this will have only a marginal effect on the total activity. Examples of radioactive substances that are currently released but for which limits are being discussed internationally are Kr-85 and C-14, mainly from reprocessing.

In addition to waste from nuclear power production, radioactive waste is also produced in Sweden by the use of radioactive substances in industry, medicine and research. By far the greatest

Table 2:2. Categories of waste

Category	Origin	Form	Properties	Quantity[1)]	Total activity[2)]
1a Spent fuel	Operation of nuclear reactors	Fuel rods encapsulated in copper canisters	High heat flux and radiation at first. Contains long-lived nuclides	4 500 canisters	10^{20}Bq
1b High-level waste	From reprocessing	Vitrified waste encapsulated in lead-titanium canisters	High heat flux and radiation at first. Contains long-lived nuclides	730 canisters	10^{19}Bq
2 Trans-uranic-bearing waste	From reprocessing	Solidified in concrete or bitumen	Low- to medium-level. Contains long-lived nuclides	4 000 m^3	10^{16}Bq
3 Core components and reactor internals	Scrap metal from reactor core	Untreated or cast in concrete	Low- to medium-level. Contains certain long-lived nuclides	5 000 m^3	10^{18}Bq[2)]
4 Reactor waste	From nuclear power plant operation etc.	Solidified in concrete or bitumen. Compacted waste	Low- to medium-level. Limited lifetime	122 000m^3	10^{16}Bq
5 Decommissioning waste	From the decommissioning of nuclear facilities	Mostly untreated	Low- to medium-level. Limited lifetime	151 000m^3	10^{15}Bq

1) Total in 2020.
2) Mainly Fe-55 and Co-60 ($T_{1/2}$ <5 years).

portion of this waste comes at the present time from the nuclear research facilities at Studsvik and contains both long- and short-lived wastes. A coordination of the final storage of this waste with waste originating from nuclear power production would appear to be expedient. SKBF is prepared to participate in bringing this about. However, the rest of this report deals only with waste from nuclear power generation.

2.3 GENERAL PRINCIPLES – OPTIONS AND LIMITATIONS

2.3.1 General

The framework for Swedish efforts for the management of radioactive wastes generated by nuclear power, including the necessary R&D work, is determined by:

- the fixed times established by Parliamentary decisions, temporary operating licences and reprocessing contracts, as referred to in section 2.1,
- the various types of waste that must be disposed of and are described in section 2.2,
- the facilities required for the handling and final storage of the wastes and the time needed for planning, design and construction, see chapter 3,
- the options and limitations consequent on the basic principles discussed below.

On the basis of current legislation and political attitudes, the following basic principles for the final storage of radioactive wastes can be established:

- It shall be possible to carry out the required measures with the highest possible degree of national independence.
- Burdens on future generations shall be avoided.
- A very high level of long-term safety is essential.

2.3.2 National independence

Assuming that the highest possible degree of national independence is desirable, it follows that the final storage shall be arranged in Sweden and using a technology that is available in Sweden. The specific conditions existing in Sweden allow only some of the methods and solutions being discussed internationally to be used here.

Table 2:3 shows some of the different general methods and storage media that have been proposed in the international discussion. The alternatives in the different columns cannot always be combined.

Table 2:3 <u>Conceivable principles and media for the final storage of radioactive waste</u>

A.	GENERAL METHOD	B.	STORAGE MEDIUM
A.1	Supervised storage	B.1	Crystalline rock - granite - gneiss - gabbro - others
A.2	Surface disposal 50 m		
A.3	Deep geologic disposal 500 m	B.2	Salt
A.4	Dumping at sea	B.3	Clay
A.5	Disposal in deep-sea sediment	B.4	Sedimentary rock types
A.6	Injection into isolated aquifers		
A.7	Disposal under inland ice sheets		
A.8	Launching into space		
A.9	Separation and transmutation		

With regard to the <u>general method</u> the following can be said:

A.1 Supervised storage can be employed for limited periods of time but does not constitute a final solution.

A.2 Surface disposal in soil layers or in the bedrock is possible for certain types of waste. Depth, storage medium and possibilities for restrictions on land use must then be considered in relation to the lifetime and toxicity of the waste. Such deposition is only suitable for short-lived waste.

A.3 Geologic disposal at depths where surface influences or climatic variations no longer affect the bedrock to any significant degree ($\geq$300 m) must be employed for long-lived waste.

A.4 Dumping at sea can be discounted, since it is prohibited by Swedish law.

A.5 There is no possibility of disposing of waste in deep-sea sediment within Swedish territorial waters.

A.6 The method of injecting liquid waste into large but isolated permeable aquifers is only of interest in countries with sufficiently thick sedimentary bedrock.

A.7 There are no inland ice sheets (glaciers) or areas of permafrost of sufficient extent in Sweden. Moreover, the method can be seriously questioned when it comes to long-lived wastes, since it is not possible to foresee climatic changes during the time spans involved here.

A.8 It is unlikely that the resources required for launching wastes into space will be available in Sweden in the foreseeable future.

A.9 The technology required for rendering radionuclides harmless through separation and transmutation is not available.

It can be concluded from the above that the preferable alternatives for Sweden are:

- a shallow geologic disposal of short-lived waste as per A.2, and
- a deep geologic disposal of long-lived waste as per A.3.

Geologic disposal (i.e. final storage) can be effected in various media (see table 2:3).

B.1 Most of the Swedish bedrock consists of crystalline rock, making this type of medium the most convenient for the storage of radioactive wastes. No types of crystalline rock (granites, gneisses, gabbros, ultramafites) should be discounted at this stage.

B.2 There are no suitable salt formations in Sweden.

B.3 There are no sufficiently extensive clay formations in Sweden.

B.4 Sedimentary rock types occur within the country but are normally limited with regard to both area and depth. Only in the province of Skåne in southern Sweden do sedimentary formations of sufficient size to accommodate a final repository exist.

It would appear that crystalline rocks are of the greatest interest for final storage in deep geological formations in Sweden. However, the sedimentary rocks in Skåne should not be discounted at this stage.

2.3.3 Burdens on future generations

It is a generally accepted principle that radioactive wastes should be disposed of in such a manner that burdens on future generations are avoided to as great an extent as possible.

In order to prevent financial burdens being placed on people who do not derive any benefit from nuclear power production today, the Financing Act stipulates that special reserves are to be set up to cover the cost of final waste disposal. However, future burdens may well be of other than a financial nature. Consideration should therefore be given to:

- the necessity of future surveillance
- the consequences of inadvertant intrusion
- demands on technological progress and
- demands on natural resources.

In order to avoid the necessity of extensive future surveillance, two principles shall guide the design of a final storage system:

- The long-term safety of the facility shall be based on principles and mechanisms whose function is not dependent on human control or influence.

- The impact of the facility on its surroundings shall be so limited that restrictions do not have to be imposed on land use after the repository has been sealed.

Consideration should be given in designing and siting the repository to future inadvertant human intrusion into the repository and the consequences thereof. Intentional intrusion, however, neither can nor need be prevented. Each generation is naturally free to make its own decisions and take responsibility for its own actions. It is conceivable, for example, that at some time in the future, it may be desirable to recover the wastes for their raw material value. In order to provide the greatest possible assistance to future generations in basing such decisions on a complete body of facts, information on the location, design and contents of the repository should be preserved in a manner that reduces the risk of its being lost.

Inadvertant intrusion presupposes that this information on the repository has been lost. Chance, or the results of geotechnical measurements, could then lead a technologically advanced society in the future to investigate and penetrate the area. However, it can be assumed that such a high level of technology cannot exist without a concomitant awareness of radioactivity and its risks as well as the capability to measure it. The risk should be minimized by not locating the repository in areas containing deposits of minerals which could be considered of value for mining in the future.

In order to avoid the risk of technologically underdeveloped civilizations stumbling on the repository by chance, the final repository should be situated at a depth that makes the probability of this happening low.

In order to avoid making unreasonable demands on future technological progress, the design of the final repository and the barriers should be based on known and proven technology or technology whose development up to the implementation stage can be foreseen.

In order to minimize effects on future supplies of important raw materials, the storage system should only make limited use of such materials.

2.3.4 High degree of long-term safety

The purpose of final storage is to protect mankind from the harmful effects of the radioactive substances present in the waste in both the short and long term.

Part of the toxicity of long-lived waste will persist for periods of time that are long compared to human experience of engineering materials. The overall safety of the system should therefore be based on a number of mutually independent barriers. The safety function of each barrier should be carefull assessed, which means that it should perform its intended function with a satisfactory margin of safety. The system shall be constructed in such a manner that overall safety is not jeopardized in the event of deficiencies in one of the barriers.

A characteristic aspect of the long-lived waste is the great difference between initial toxicity and residual long-lived toxicity, as well as the very long period of time during which the toxicity exists. For those barriers that are to function over a very long period of time, geological evidence should supplement human experience.

Safety is normally evaluated in the light of society's criteria and norms. However, many aspects of final storage encompass time spans of the same magnitude as those required for the evolution of new species. It should therefore also be shown that the long-term impact of the repository on its environment does not essentially alter natural radiological conditions in the region.

3 FACILITIES

3.1 GENERAL PREMISES

The various facilities that are currently planned to be included in the system for the management and disposal of the radioactive wastes from nuclear power generation have been designed and sized on the following premises.

1 The scope of the Swedish nuclear power program is as described in section 2.1 and is assumed to give rise to the types and quantities of waste indicated in 2.2.

2 Nuclear fuel reprocessing is carried out to the extent provided for in existing contracts (867 t U). The rest of the spent fuel will be disposed of directly.

3 Spent fuel and high-level waste from reprocessing will be placed in intermediate storage for approximately 40 years in order to limit heat flux in the final repository.

4 High-level waste and spent nuclear fuel will be finally disposed of in deep-lying repositories in crystalline rock with an isolation system based on the multiple barrier principle.

5 Long-lived low- and medium-level wastes from reprocessing will also be placed in intermediate storage for approximately 40 years so that final disposal can take place at the same time as the final diposal of the high-level waste.

It is possible that these premises may come to be changed or modified in the light of the results of continued R&D work or as a consequence of future political decisions. However, the system of facilities outlined here constitutes a technically feasible solution based on current know-how and national policies.

3.2 OVERALL SYSTEM

The premises set forth in the preceding section lead to the system of facilities illustrated schematically in Figure 3-1.

The various parts of the system are in very different stages of realization. As regards the most imminent of these - CLAB and the transportation system, scheduled for start by 1985 and 1982, respectively - construction of the former and manufacture of the latter are currently in progress. In other words, the detailed design of these facilities has already been determined in essential respects. The next step in the realization of the system involves the construction of a final repository for reactor waste, SFR. Licencing applications have been submitted to the appropriate authorities in the spring of 1982, and the facility is expected to be commissioned in 1988. Provided that the approval of the authorities is obtained, the main features of this facility can also be considered to have been finalized.

Intermediate storage facilities for reprocessing waste (CLG and CLU) will be needed by 1990, and work has already begun on preliminary planning and design. As regards treatment plants (BSG and BSAB) and final repositories for long-lived waste products (SFL), current plans call for siting decisions around the year 2000 and commissioning of the facilities in 2020.

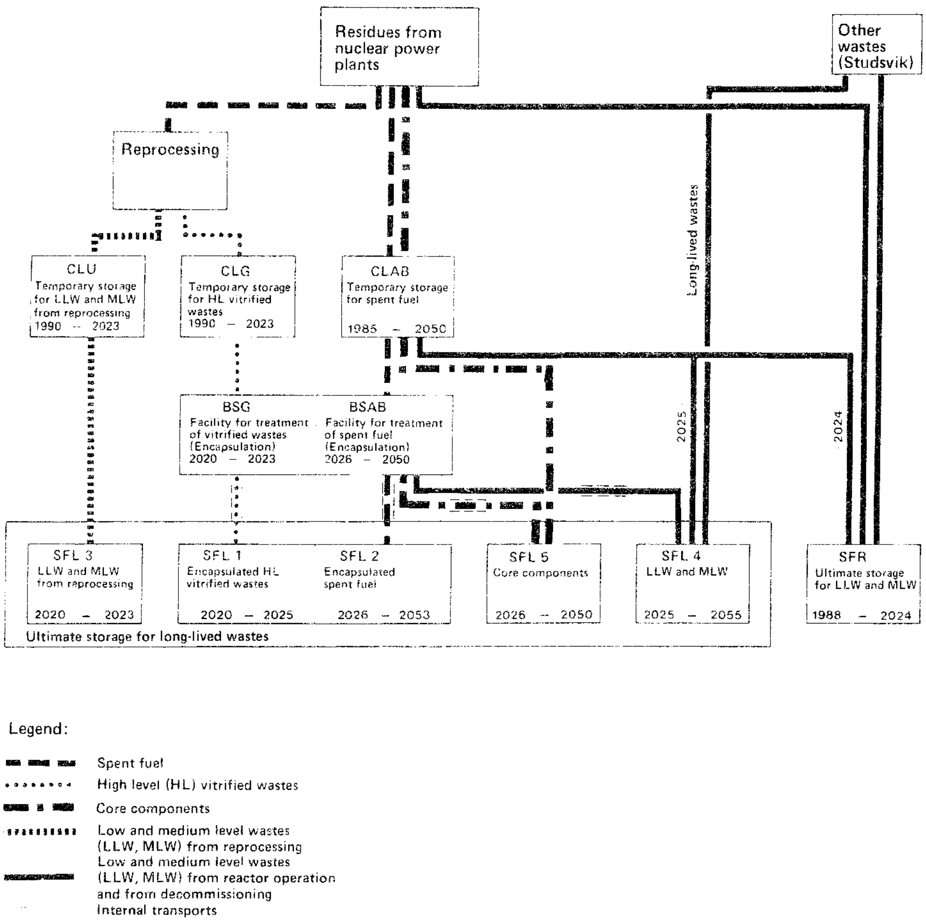


Figure 3-1. Facilities and handling sequence for residual products from nuclear power generation.

Extensive specific investigations at various sites are expected to precede a siting decision. Similarly, a considerable amount of work remains to be done for these facilities in the form of studies of alternative solutions for the various parts and successive optimization and detailing.

3.3 INDIVIDUAL FACILITIES

The individual facilities included in the system, their siting and their scheduled start of operation are presented in Table 3:1.

Table 3:1 Facilities for treatment and final storage of nuclear power waste

Facility	Foreseen location	Scheduled start of location	Notes
1. Transportation system	-	1982	Comprises specially designed ship, transport casks and terminal facilities
2. Intermediate storage facilities			
2.1 CLAB. Central storage facility for spent fuel	Oskarshamn	1985	3 000 tonnes of fuel in an initial phase.
2.2 CLG. Central storage facility for vitrified waste	Co-siting with 2.1 or 4.1 considered suitable	1990	730 vitrified waste units
2.3 CLU. Central storage facility for transuranic-containing waste	Co-siting with 2.1 or 4.1 considered suitable	1990	Approx. 4000 m^3 of waste
3. Treatment facilities			
3.1 BSG. Treatment station for vitrified waste	Co-siting with 4.2 considered suitable	2020	Encapsulation station with capacity to treat 730 vitrified waste units during the period 2020-24
3.2 BSAB. Treatment station for spent fuel	Co-siting with 4.3 considered suitable	2026	Encapsulation station with capacity to treat approx. 6000 tonnes of spent fuel during the period 2026-2050
4. Final repositories			
4.1 SFR. Final repository for operating and decommissioning waste	Proposed location: Forsmark	1988	Operating waste (SFR 1) approx. 100 000 m^3. Decommissioning waste (SFR 3 later expansion) approx. 140 000 m^3
4.2 SFL 1 Final repository for vitrified waste	To be decided around the year 2000, based on results of geological surveys	2020	730 encapsulated waste units
4.3 SFL 2. Final repository for spent fuel	Co-siting with 4.2	2026	4500 canisters, each containing about 1.4 tonnes of spent fuel
4.4 SFL 3 Final repository for transuranic-bearing waste	Co-siting with 4.2	2020	Approx. 4 000 m^3
4.5 SFL 4. Final repository for low- and medium-level operating and decommissioning waste	Co-siting with 4.2	2025	Replaces 4.1 (SFR) from year 2025
4.6 SFL 5. Final repository for core components etc.	Co-siting with 4.2 or possibly 4.1	2025	

Descriptions of the different facilities can be found in Part 2 of this report. Only brief comments are given below on the importance of the different facilities in the overall system and on their scheduling in time.

3.3.1 Transportation system

The transportation system is based primarily on sea transports, and its main components are a specially designed ship, transport casks and terminal equipment at the power plants and at the facilities for final disposal. The system is designed to cope with all types of waste produced.

The transports of spent fuel from Sweden to France are planned to commence in late 1982. This means that the ship, the transport casks and the terminal vehicles must be available at that time. The ship has been launched, one terminal vehicle has been manufactured and transport casks are in the process of being fabricated.

For the transportation of reactor waste, the system has to be supplemented with special transport casks made of concrete as well as special transport casks for core components.

3.3.2 Central storage facility for spent fuel, CLAB

An intermediate storage facility for spent fuel is needed for two reasons. The first is that some of the spent fuel pools at the nuclear power plants are expected to be filled by the mid-1980s. An expansion of these pools would be both technically complicated and very expensive. A central intermediate facility for all the Swedish nuclear power plants has been found to be a more advantageous solution. The CLAB is therefore being built and is scheduled to be ready to be put into operation in 1985.

The second reason for constructing an intermediate storage facility for spent fuel is that it is desirable that the fuel that is to be disposed of directly should not emit too much heat when it is placed in the final repository. Intermediate storage for a period of 40 years will reduce the heat flux by about 50% compared to the heat flux after 10 years of storage.

The version of the CLAB currently under construction will provide a storage capacity of approximately 3 000 tonnes of fuel. An expansion of the pools may be necessary in the mid-1990s. Core components which are not scheduled for final disposal until the 2020s will also be temporarily stored in the CLAB.

According to current plans, the CLAB will be kept operational until the year 2050, so it can reasonably be assumed that a large portion of the equipment will have to be replaced.

3.3.3 Central storage facility for vitrified waste, CLG

This storage facility fills the same basic function within the system as the CLAB, namely to provide an opportunity for the heat flux from the waste to decline prior to final deposition.

The time schedule for the CLG is determined by the reprocessing contract between SKBF and Cogema, which states that it shall be possible to send vitrified waste to Sweden in 1990. With this in mind, preliminary studies of different solutions have been initiated during 1982.

The actual design work is expected to be completed during 1984 and 1985, leaving four years for construction.

According to present-day plans, the CLG will be kept in operation until 2024.

3.3.4 Central storage facility for low- and medium-level (transuranic) waste from reprocessing, CLU

As is the case with high-level vitrified waste, the reprocessing contract between SKBF and Cogema provides that SKBF must be prepared to accept other waste from reprocessing as well in 1990. This waste will contain varying quantities of radionuclides with very long half-lives (α -emitting transuranic elements). Similar demands are therefore made on the long-term function of the barriers in the final repository as for vitrified waste. For practical and economic reasons, the final deposition of the low- and medium-level transuranic-bearing waste should therefore be coordinated geographically and chronologically with the final disposal of the high-level waste. This means that intermediate storage will be required up to the 2020s.

It is assumed that the planning, construction and operation of the CLU will run parallel to that of the CLG.

3.3.5 Encapsulation station for vitrified waste, BSG

It is assumed that the vitrified waste will be encapsulated in canisters made of a corrosion resistant material prior to final deposition. Encapsulation will take place at the BSG. Different materials will be studied, but the current assumption is a canister of lead surrounded by titanium (KBS-1). The purpose of the canister is to isolate the waste totally from its surroundings during the period when it is still highly radioactive and emits considerable quantities of heat, and to disperse the release of activity in time in a later phase. Such a dispersal will be achieved by the fact that penetration of the individual canisters will take place at different points in time.

The BSG is needed when final disposal will commence, i.e. in the year 2020. Detailed planning, design and construction are expected to be carried out during the 2010s.

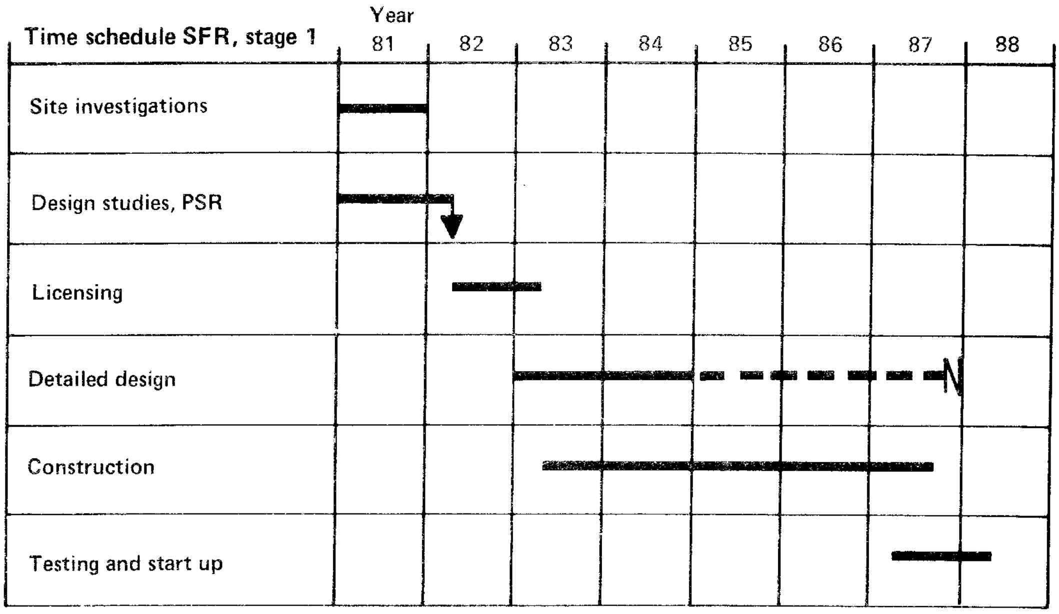


Figure 3-2. Timetable for SFR, stage 1.

For the time being, it has been assumed that the BSG will be kept in operation during the period 2020-23, when all vitrified waste will be finally disposed of. The facility will subsequently be rebuilt for the encapsulation of spent fuel (BSAB).

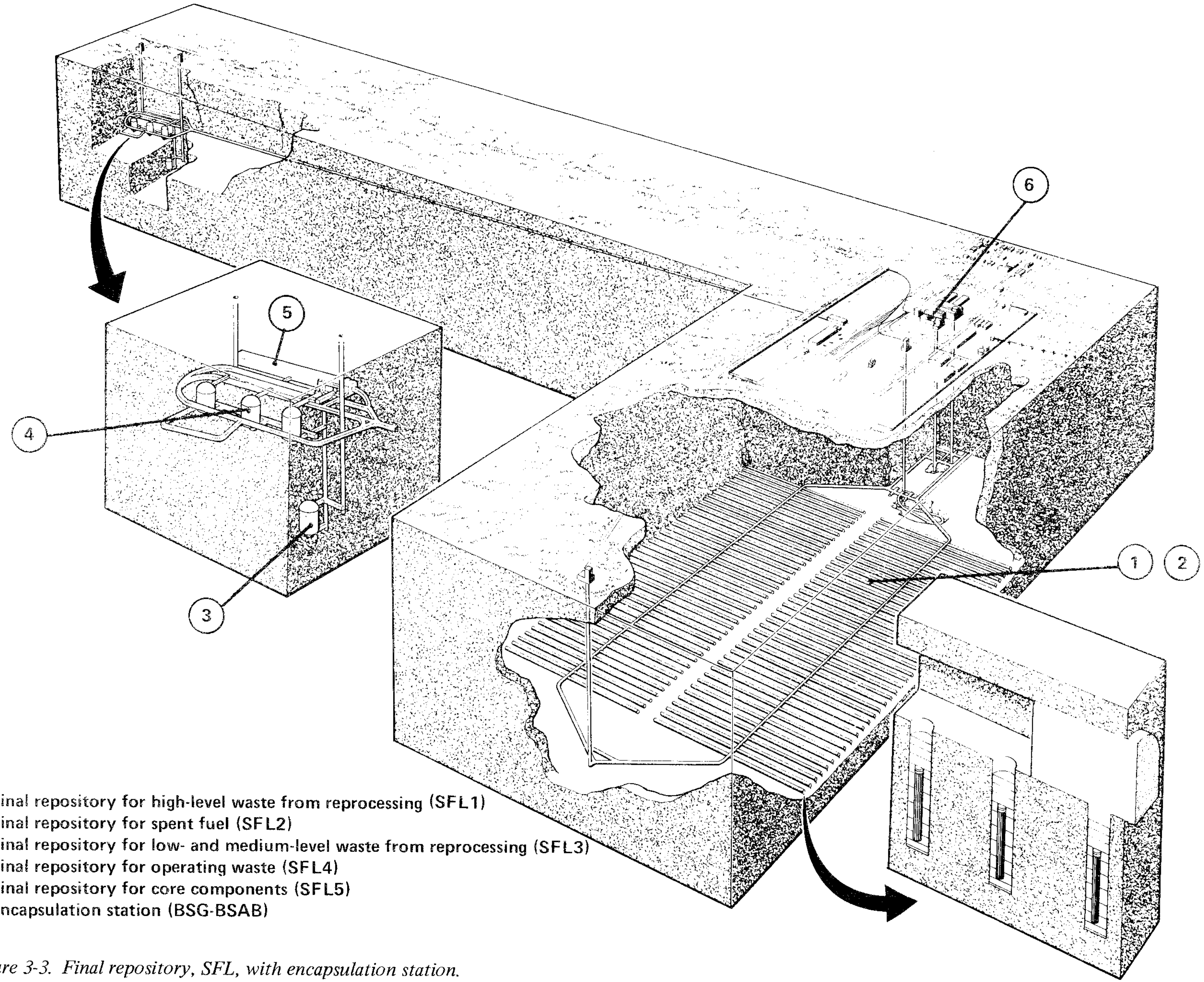
3.3.6 Encapsulation station for spent fuel, BSAB

The spent fuel will be encapsulated in canisters of corrosion resistant material in the same way as vitrified waste. It is currently assumed that a thick-walled copper canister (KBS-2) will be employed for spent fuel. Studies of other materials and designs will be carried out.

The BSAB, which is a rebuilt version of the BSG, has a planned operating period of from 2026 to 2050.

3.3.7 Final repository for waste from reactor operation and decommissioning, SFR

Operating waste, i.e. waste originating from reactor operation, is produced continously by an operating nuclear power plant. Similar waste will also be generated by the operation of the CLAB. The waste, which is low- and medium-level, does not contain long-lived radionuclides in any significant quantities. This waste is currently being temporarily stored at the power plants. A further expansion of these storage facilities should be avoided for practical and economic reasons. In the spring of 1982, SKBF has therefore applied for permission to build a final repository for these waste categories at Forsmark. The current timetable for the initial stage of the SFR is shown in Figure 3-2. A second stage is planned before the end of the century.



1 Final repository for high-level waste from reprocessing (SFL1)
2 Final repository for spent fuel (SFL2)
3 Final repository for low- and medium-level waste from reprocessing (SFL3)
4 Final repository for operating waste (SFL4)
5 Final repository for core components (SFL5)
6 Encapsulation station (BSG-BSAB)

Figure 3-3. Final repository, SFL, with encapsulation station.

The intention is to add later to the SFR a section for the final disposal of waste originating from the decommissioning of the nuclear power plants. This expansion will be made a few years into the 21st century.

It is envisaged that the SFR will be kept in operation until 2024. Low- and medium-level waste from the operation of CLAB after that year and waste in connection with the decommissioning of the BSAB is planned to be disposed of adjacent to the final repository for long-lived waste (SFL). The reason for this is that a more efficient handling procedure can be achieved if the activities are concentrated to one place.

3.3.8 Final repository for long-lived waste, SFL

The SFL is the final station for all long-lived waste as well as certain other wastes that will also be directed here for practical reasons. The facility comprises the following parts (see also Figure 3-3):

- SFL-1, Final repository for vitrified waste, which is expected to be filled during the years 2020-25.

- SFL-2, Final repository for spent fuel, where deposition is planned to proceed during the period 2026-53.

- SFL-3, Final repository for reprocessing waste (excl. glass), which is planned to receive waste during the years 2020-24.

- SFL-4, Final repository for operating and decommissioning waste during the period 2025-55 (replaces SFR).

- SFL-5, Final repository for core components.

Sealing of the various parts of the SFL is planned to take place successively during the 2050s, and the final use of the SFL will be to receive decommissioning waste from the CLAB and the BSAB, which is expected to occur towards the end of the 2050s.

4 RESEARCH AND DEVELOPMENT

4.1 GENERAL

The aim of the R&D work is to build up a sufficient fund of know-how and experience to be able to:

- evaluate the feasibility and safety aspects of different ways of handling and storing radioactive waste,
- select a system that provides a satisfactory level of safety, and
- implement the system in a technically and economically optimum manner.

The discussion below concentrates on the first point, i.e. R&D for the evaluation of different methods.

SKBF's research program has thus far focussed mainly on the final storage of high-level waste and spent fuel. Gradually, increasing attention will also be directed towards the special problems associated with the final storage of transuranic waste from reprocessing. The planning of this work is in progress, but as yet the plans are not as detailed as those for high-level waste and spent fuel. The following presentation therefore concentrates mainly on the latter categories of waste.

The final storage can, in principle, be carried out in a variety of ways. As was pointed out in Chapter 2, certain conditions in Sweden have limited the studies primarily to final storage in crystalline bedrock.

The time at which disposal of the long-lived waste will commence, the year 2020, has been chosen in order to allow for a decay period of 40 years between the discharge of the fuel from the reactor and its final disposal. This also provides sufficient time for a thorough review and selection of alternative storage methods and repository locations and a testing of systems and

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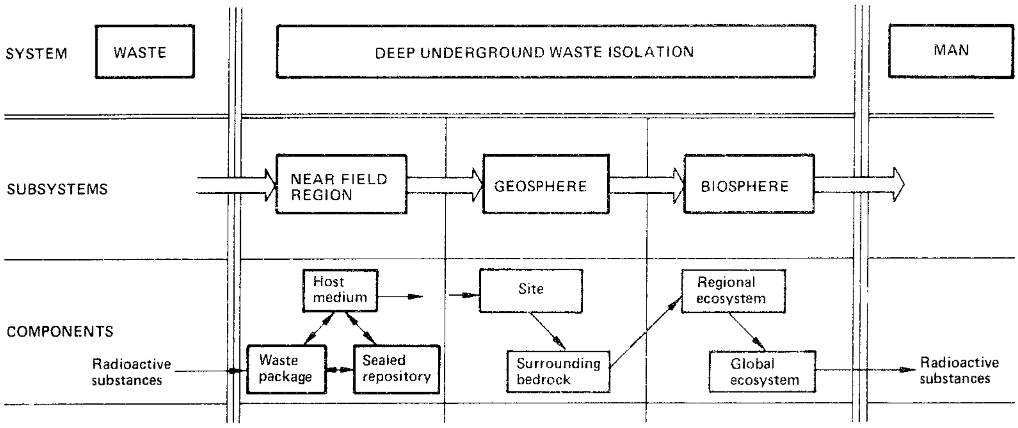

Figure 4-1. Schematic structure of the final storage system.

methods, including the possibility of pilot plants. The intermediate storage period can be varied by ±10 years without any particular complications.

The purpose of a final repository is to contain the waste so that the radioactive substances cannot reach human beings in harmful quantities. In order to achieve this, the storage system must meet two requirements. The first is to isolate the waste from the groundwater during the period when the heat flux, radioactivity and toxicity of the waste is high. The second is to restrict the rate at which the remaining low-level but long-lived substances are released.

The overall system for final storage in rock is illustrated in Figure 4-1.

The different subsystems show the fundamental differences between the available alternatives. Irrespective of how the final waste storage is effected, essentially the same biosphere can be considered to constitute the ultimate interface with mankind, since present-day regional differences cannot be expected to persist in the time perspectives involved here. The geosphere can be assumed to retain its characteristics, at least in stable regions of bedrock, during the eras under consideration. Different types of rock and different depths, as well as variations in the hydrogeological characteristics of the storage sites, can entail differences in the importance of the geosphere for safety.

The design of the third subsystem, the near field, is open to greater option. Judging from what is known at present, it would appear that the required function of a near field can be achieved through several different combinations of individual barriers.

In the following sections, the R&D work is presented under the headings given below.

4.2 Properties of wastes
4.3 Near field
4.4 Geosphere
4.5 Biosphere

Certain superordinate activities are then dealt with under these headings:

4.6 Methods for safety analysis
4.7 System and facility design

Each field of research is introduced by a brief section on its importance for the final storage scheme and the current state-of-the-art within the field. A more detailed picture of current research activities can be obtained from the KBS annual report for 1981 (TR 81-17). Subsequent sections deal with the need for research activities that can be expressed in concrete terms today. The detailed program of these activities must be continuously reevaluated in the light of the results of scientific and technological advances as well as the targeted studies that are being conducted by SKBF or equivalent organizations in other countries.

On an international level, work is being conducted on the formulation of guidelines for the design of final repositories, particularly within the IAEA. These guidelines can be expected to be of the following general character:

> "The repository should be designed, constructed and operated to minimise any adverse effects due to the repository development including the emplaced wastes on the radionuclide retardation capability of natural geological and hydrogeological systems."

Work has been started in a number of countries to establish more quantitatively precise criteria. At the present time, there is no definitive system of criteria in existence anywhere.

Responsibility for establishing criteria rests with the national safety authorities in the different countries. There is an extensive exchange of views between different countries.

Certain internal criteria of a general nature have been applied in the work done so far in Sweden, for example that an attempt should be made to find a sufficiently extensive rock formation with low and slow groundwater turnover, regions containing deposits of valuable minerals should be avoided etc. Only one quantitative criterion has been applied, namely that the temperature of the canister surface shall at no point exceed 100^{o}C. The purpose of this is, firstly, to make it easier to prove the long-term stability of the buffer material and, secondly, to limit temperature-induced rock stresses. Another purpose is to prevent boiling of the groundwater which can come into contact with the canister when the repository is still under atmospheric pressure. These internal criteria must not be regarded as prerequisites for achieving a safe final storage.

SKBF is participating in and following the work of establishing general guidelines for final repositories that is being conducted within the IAEA and the OECD/NEA. Even though they may be formulated in rather general terms, such internationally accepted guidelines are considered to be of great importance for an international exchange of views and mutual understanding. The time is not quite ripe, however, for the formulation of more precise and quantitative criteria.

4.2 PROPERTIES OF WASTES

This section deals with:

- methods for the treatment of the waste to convert it into a form suitable for handling, transportation, storage and final disposal,

- characterizing different types of waste with regard to physical properties, chemical form and content of radioactive substances.

The objectives of the studies are to define the quantities of radioactive substances, decay heat, radiolysis and leaching properties in order to provide a basis for evaluating different treatment methods from the viewpoint of final storage, and to define the preconditions for chemical interaction in the near field.

Wastes are dealt with under the following headings:

- High-level waste
- Transuranic waste
- Reactor waste

4.2.1 High-level waste

Sweden has two forms of high-level waste to consider at present: spent nuclear fuel and vitrified waste from reprocessing.

In the light of the contract with Cogema and the limited scope of the Swedish nuclear power program, the development of other forms of waste is only of indirect interest. International developments are, however, followed closely.

Extensive research is being conducted internationally on vitrified high-level waste. Swedish research efforts up to 1985 have been planned on the basis of the timetable for the return shipment of waste glass from Cogema. Much of this research work falls within the framework of a joint project between Japan, Switzerland and Sweden, called the JSS project, see section 7.3. The studies are concentrated on the interaction between the waste glass and the surrounding materials in the repository environment.

As regards spent fuel, international activities are more limited at the present time. However, some leaching studies are currently being conducted in Canada, France, Germany and the United States.

Ongoing and planned Swedish research includes leach tests in oxidizing and reducing environments. A special international reference group has been assembled to follow the tests and evaluate the results.

The quantity of radioactive substances in the fuel is calculated with the aid of established mathematical models.

Future research within the field of high-level waste will be concentrated on mechanisms and kinetics for the liberation of radionuclides from the waste matrix.

The main organizations engaged in the KBS studies of high-level waste are Studsvik Energiteknik, the University of Florida, the Department of Inorganic Chemistry at the Royal Institute of Technology in Stockholm, the Swedish Glass Research Institute in Växjö and EIR, Switzerland.

4.2.2 Transuranic waste

In addition to the high-level vitrified waste, various types of low- and medium-level waste are obtained from reprocessing. Some of these wastes contain long-lived α-activity (transuranic elements) in the same concentrations as the vitrified high-level waste. Heat flux is considerably lower, however.

A containment matrix has not yet been established for the transuranic waste. At present, attention is being concentrated on cement and bitumen matrices, but other matrices may also be considered. SKBF's activities will be adapted to the specifications that will be established and the investigations that are being carried out by the reprocessor Cogema. An initial description of the waste forms will be submitted during 1982/83.

Up to now, work has been concentrated primarily on identifying the questions that will be of interest in connection with the final storage of long-lived waste solidified in concrete and bitumen. Examples of such questions are:

- The chemical form of the activity in the waste.

- The effects of high pH (cement) on the solubility and transport properties of the radioactive substances in the matrix and in the surrounding buffer material and rock.

- The risk of the formation of gas and organic complexing agents in connection with the decomposition of organic waste and bitumen.

- The effects of radiolysis.

- Long-term changes in cement and bitumen.

- The interaction between concrete and buffer material.

Work during the coming 5-year period will be governed by the fact that approval of the waste by the Swedish authorities is required before the reprocessing of Swedish fuel may commence at UP 3 in La Hague. The aim is that a report on how the wastes are to be managed shall be presented during 1985-86. Current work is primarily being carried out at the Department of Nuclear Chemistry at Chalmers University of Technology, the Swedish Cement and Concrete Research Institute and Studsvik Energiteknik AB.

4.2.3 Reactor waste

Reactor waste is being treated at the power plants, and development of treatment methods is normally conducted by the nuclear power companies. SKBF's activities within this field are aimed primarily at verifying the fact that the waste products obtained in this manner are suitable for final storage in the SFR. In addition, SKBF carries out development work of common interest to the power companies.

4.3 NEAR FIELD

By "near field" is meant the space in which the waste is deposited and the adjacent rock sections that might be affected by the intrusion entailed by the final repository. The material transport that takes place in the near field with its contents of waste, canister material and buffer mass differs essentially from that which takes place in the unaffected parts of the geosphere.

The near field is considered below with reference to the following components:

- encapsulation
- buffer and backfill
- design of repository

This section is concluded with

- near-field chemistry

which deals with the chemical interaction between the constituent materials.

4.3.1 Encapsulation

The primary object of encapsulating the radioactive waste is to create an absolute barrier against the dispersal of radioactive substances during the initial period of storage. In addition, the canister serves as a radiation shield that reduces radiolysis of the groundwater and facilitates handling.

Materials

Two essentially different types of materials and combinations of them appear to be of most interest for the encapsulation of high-level waste:

- Metallic materials
- Ceramic and vitreous materials

SKBF's work is currently focused mainly on studies of metallic materials.

The resistance of metals to corrosion may depend either on their thermodynamic stability in water (copper) or on the formation of a passivating surface film (titanium). In view of the long storage times that are required for spent nuclear fuel and vitrified high-level waste from reprocessing, SKBF has chosen to concentrate for the time being on copper, which possesses high thermodynamic stability.

Studies of other metallic materials - for example iron, steel and titanium - as well as ceramics are currently being conducted at a number of laboratories abroad. SKBF is following the progress of this work.

SKBF's own studies are at present concentrated primarily on different forms of copper corrosion (pitting, stress corrosion etc.) in a reducing environment. Work is being conducted in the following fields:

- stress corrosion in copper at the University of Newcastle-upon-Tyne in England,

- archeological/geological evidence of pitting in copper and copper alloys, primarily at the Archeological Research Laboratory at the University of Stockholm,

- the corrosion resistance of copper in the disposal environment; the Swedish Corrosion Institute is responsible for this work and has established a special expert group for the purpose,

- the passive film on titanium; the Department of Metallic Engineering Materials at Chalmers University of Technology is doing most of this work.

Further studies of different metals and ceramics that may come under consideration as encapsulation materials are envisaged in the five-year plan. The possibility would not appear to be ruled out that considerably simpler canister materials than copper could prove to be adequate for the purpose. This possibility will be largely dependent on what results are obtained from the studies of near-field chemistry.

Encapsulation technology

Two different methods for containment in copper are currently being studied for the encapsulation of spent nuclear fuel.

The first method involves a further development of the technique described in KBS-2, where the fuel rods are embedded in lead inside a prefabricated copper canister, after which a lid is welded onto the canister.

The other method involves the use of hot isostatic pressing (HIP). This process has previously been tested for the manufacture of ceramic canisters made of aluminium oxide. Experiments are currently being conducted to enclose spent fuel in copper using the HIP process. In this method, fuel elements with their metal components are placed in a copper canister, after which the surrounding space is filled with copper powder. A lid is placed on the canister and the entire assembly is pressed into a solid body.

The five-year plan calls for continuous studies of important aspects of the encapsulation technology, for example current studies include:

- test welding of thick copper at Sciacy, Leybold-Heraeus and the Welding Institute,

- method development of the HIP process of enclosing spent fuel in copper at ASEA in Robertsfors,

- follow-up of lead technology.

Alternative canister designs will also be studied, as well as the possibility of distributing broken-up fuel in a suitable matrix material.

Concrete technology

It has been proposed that some long-lived radioactive waste from reprocessing, along with long-lived radioactive metal components from the fuel core, should be enclosed in concrete.

Studies of the conditions near the interface between concrete and clay have been initiated, and similar studies are being conducted abroad. Preliminary results indicate that the degradation of concrete under storage conditions is a very slow process.

The main emphasis of the work to be carried out in the next few years will be on the acquisition of basic knowledge of materials and their long-term resistance rather than on design.

It is expected that most of the work will be done by the Swedish Cement and Concrete Research Institute and New York State University.

4.3.2 Buffer and backfill

By "buffer" is meant here the filling material that surrounds the waste canisters and fills out the space between the canisters and the walls of the deposition holes. By "backfill" is meant the filling material that replaces the excavated rock volume in tunnels, shafts and boreholes.

Sealing of boreholes, tunnels and shafts are dealt with in section 4.4.5.

The properties of the buffer and backfill that are of primary interest are their ability to prevent groundwater flow, their chemical and mechanical protective capacity and their thermal conductivity.

Knowledge of long-term stability over periods of time as long as 100 000 years and more can be obtained from studies of similar naturally-occurring materials and from studies of the fundamental processes that can affect the properties of the material.

SKBF has conducted relatively comprehensive investigations of clay buffers, primarily those based on bentonite of the Wyoming type. Similar investigations have recently been begun in Switzerland and the United States, among other countries. The Swedish studies will continue and will be pursued to greater depth and extended to include investigations of domestic clay materials.

The behaviour of the buffer and the backfill is being studied in the large-scale "Buffer Mass Test" that is currently being conducted in Stripa (see Section 7.2).

During the next few years, studies will be made of, among other things, the rheological properties of clay gels of varying density, temperature and electrolyte content, and their stability in contact with groundwater.

Studies of alternative buffer materials and additives (for example getters) are planned. Among other things, the possibility of surrounding the canisters with lead applied directly in the deposition holes should be studied.

The Division of Soil Mechanics at the University of Luleå is the principal consultant for studies of buffer and backfill.

4.3.3 Design of repository

The detailed geometric design of the repository may be of importance for conditions in the near field in that it influences the temperature field and the stress picture. The surrounding rock is damaged to a certain extent during excavation. Such damages can be limited by using a method known as full-face driving for constructing the storage tunnels.

So far, stress calculations have been carried out with the aid of FEM analysis for the repository types referred to in KBS-1 and KBS-2. Similar analyses have been carried out for a number of foreign repository concepts. Stress and deformation measurements have been carried out on full scale in Stripa, among other places.

Further R&D work is required within the following fields:

- The effects of different repository designs on the temperature field.

- The temperature field and stability of different types of rock.

- Different methods of driving tunnels (blasting, full-face driving) and their effects on the hydraulic conductivity of the rock.

- The effects of different building materials and possible impurities on conditions in the near field.

Studies of repository designs that differ radically from those proposed in KBS 1 and 2 are also envisaged, for example deposition in deep boreholes.

The Department of Mining and Civil Engineering at the University of Luleå is the principal consultant for the studies of rock mechanics.

4.3.4 Near-field chemistry

The near field chemistry treats the interaction between the various components of the repository.

These studies have three main objectives:

- to show how chemical changes in the near field influence the near field's barrier functions and the properties of the geosphere,

- to determine the rate of the processes that can govern the corrosion of the canister,

- to determine when, how fast and in what form radionuclides can leave the near field and begin to be transported with the groundwater in the geosphere.

Geochemical model calculations is one way to obtain information on the stability of various components in the near field and this approach is followed in the United States, Canada and Switzerland.

In order to be able to determine in what form and in what maximum concentration the radionuclides can be transported out of the near field, it is necessary to understand the interactions of these substances (redox reactions, complex formation, dissolution, precipitation, co-precipitation and colloid formation) with other substances in the near field (rock, buffer, groundwater and waste matrix). Of particular importance in this context are the actinides and technetium. The acquisition of a greater knowledge of basic chemical data as well as fundamental studies of complex and colloid formation under different environmental conditions in the near field will thus be given high priority in the continued work.

Work is currently in progress to calculate the effect of radiolysis and verify these calculations experimentally. Hydrogen diffusion in bentonite, as well as the concentration and availability of bivalent iron in bentonite and surrounding rock, are important parameters in the radiolysis studies.

An important function of the buffer is to prevent flowing water from reaching the waste canister or the waste. All transport of dissolved substances to or from the waste must take place via diffusion through the buffer mass. Most of the transport resistance for non-sorbing species occurs at the interface between the buffer and the slowly-flowing water in continuous rock fractures. The supply of groundwater around a deposition hole constitutes an important boundary condition.

Transport models for the near field are being developed in Sweden and the United States.

The diffusion of hydrogen sulphide ions and colloids in highly compacted bentonite is being studied in collaboration between the Department of Nuclear Chemistry at the Royal Institute of Technology and the Department of Geophysics at the University of Luleå. The importance of adding getters to increase the sorption capacity as well as the diffusion of actinides are being studied at the Department of Nuclear Chemistry at Chalmers University of Technology. Diffusion experiments in clays are also being conducted in the United States, Canada, Switzerland and Belgium.

Calculations on the effects of radiolysis are being carried out at Studsvik in parallel with radiolysis experiments at the Department of Nuclear Chemistry at the Royal Institute of Technology.

An overall chemical characterization of the near field is being carried out at Risø in Denmark and will be completed by the end of the year. This work also involves model computations.

Solubility, complex formation, redox equilibria and colloid formation, with particular emphasis on actinides, are included in the research work contracted out to the Department of Inorganic Chemistry at the Royal Institute of Technology and the Department of Nuclear Chemistry at Chalmers University of Technology.

Basic groundwater chemistry studies based on water and mineral samples from the study areas will be conducted at Louis Pasteur University in Strasbourg.

The chemical characterization of the near field and the basic studies of the chemistry of the actinides are expected to continue throughout the entire five-year period.

A continuous investigation of the chemistry of the near field and its significance for the long-term performance of the repository is foreseen for a number of years to come. Planning will be tied to the rate at which new and improved basic data are obtained.

4.4 GEOSPHERE

By "geosphere" is meant in this context the natural bedrock with its cracks and fracture zones and the groundwater in the rock, which constitutes the transport medium for radionuclides from the repository to the biosphere.

The near field ends where natural conditions are no longer appreciably affected by the repository. The biosphere begins where the nuclide transport is dominated by ecological relationships in the biosphere.

The section is divided into the following subsections:

- Groundwater movements
- Radionuclide dispersal
- Geological stability
- Instruments and methods for data collection
- Methods for sealing of boreholes, tunnels and shafts
- Site investigations

4.4.1 Groundwater movements

Knowledge of the bedrock and its structure as well as the flow of groundwater in fractures is one of the fundamental prerequisities for the assessment of the safety of a final repository. Research aims at shedding light on travel times and transport pathways of radionuclides in the groundwater on their way from the repository through the rock mass to the biosphere.

In order to calculate flow quantities and groundwater flow times, knowledge is required of the groundwater gradient and the hydraulic conductivity and porosity of the rock mass. Hydraulic conductivity and porosity vary in the rock mass, depending on the structure of the rock matrix and the presence of continuous fracture systems.

Among the aims of current research is to better define and classify existing fractures and fracture zones, since it is in these that most of the groundwater flow take place. Tracer experiments have been conducted at Finnsjö Lake and Studsvik in order to obtain a greater understanding of hydraulic conductivity and dispersion as well as of the influence of porosity and fracture width on these parameters. Additional tracer tests have been initiated in the low-permeability granite in Stripa. Different methods for determining hydraulic conductivity have been analyzed and tested. Geophysical cross-hole measurements aid in locating fracture zones. Work on the development of electrical, electromagnetic and seismic methods for this purpose has begun and will continue throughout the coming five-year period.

A mathematical model for simulating three-dimensional hydro-thermal groundwater flow has been developed. The model takes into consideration the heat flux from the repository, changes in the viscosity of the groundwater and anisotropy of the hydraulic conductivity.

The goal of the long-term research program is to improve the methods used for calculating groundwater flow.

A development of methods for the measurement and interpretation of groundwater movements in crystalline rock will proceed in parallel with the site investigations described in section 4.4.6.

KBS is also following the results of research activities within these same fields in other countries.

The Geological Survey of Sweden has been engaged as the principal consultant for most of the research work concerned with ground-water flow in bedrock. Model development is being conducted primarily at the Department of Land Improvement and Drainage at the Royal Institute of Technology.

4.4.2 Radionuclide dispersal

The flowing groundwater will be the transporting medium for radioactive substances in the geosphere.

Calculations of radionuclide transport are based on hydrogeological flow calculations, whereby the retention and retardation of the various radionuclides as a result of sorption and precipitation are taken into consideration. Allowance must also be made in this context for nuclide transformation due to radioactive decay. The calculations give the rate at which and the concentrations in which the radionuclides reach the biosphere.

The chemical interactions in the near field determine when, how fast and in what chemical form the nuclides will escape into the geosphere.

A geochemical characterization of the far field will be carried out in connection with the site investigations. Geochemical model computations on the origin and evolution of groundwater and fracture-filling minerals, of importance for the repository performance, are being conducted mainly in the United States, but work has also gotten underway in Canada, Switzerland and France.

Sorption is influenced by the charge and valence of the ions. The strongest sorption is exhibited by highly charged metal ions. However, due to their higher polarity, they also have a tendency to form aggregates with different charge and different sorption properties. There is also a strong correlation between solubility and sorption. Actinides generally have low solubility and a strong tendency to get sorbed under reducing conditions typical for deep groundwaters.

Complex formation is of great importance for the transport process. The most important naturally-occurring complexing agents are carbonate and hydroxide ions. Complex formation between organic material in the groundwater (humic and fulvic acids) and actinides is of less importance for of deep-lying repositories.

Radionuclides in the form of colloids or pseudocolloids can potentially reduce sorption in geological systems.

Continued work is being concentrated on the elements Th, Pa, U, Np, Pu and Tc, which are essential to the safety analysis. Redox and complex formation reactions, as well as the influence of the various fracture-filling minerals, are being investigated in the experiments. Special efforts are made to obtain better data on Np, Pu and Pa. The mobility and sorption of colloidal species are being studied as well.

International efforts have been massive as regards sorption experiments. An OECD-NEA project, ISIRS, is aimed at collecting and organizing the available information, and SKBF is participating in this work.

Laboratory measurements together with observations of undisturbed rock in nature show that nuclides can diffuse from the larger water-bearing fractures through the fracture surface minerals into the system of microfractures within the rock. The fracture surfaces in the grain boundaries sorb the radionuclides in the same manner as the surfaces in the larger fractures. This provides a very large surface area for sorption and the effect of this mechanism on the retardation of the groundwater-transported radionuclides is decisive.

Work is currently being conducted to measure the porosity and diffusivity of the rock matrix, the permeability of the fracture surface minerals and the influence of rock pressure on these parameters.

In order to verify model computations, theoretical assessments and laboratory experiments, in-situ tests are being conducted with tracers.

The geochemical characterization of the rock and the groundwater, as well as the basic studies of the chemistry of the radionuclides and their retention in the geosphere, are expected to continue throughout the entire five-year period.

International developments in this and closely-related fields will be followed closely. The following basic plan for Swedish research activities will be followed.

- Geochemical studies of groundwater aimed at describing redox conditions, solubility and complex formation are being conducted at the Department of Inorganic Chemistry at the

Royal Institute of Technology. Water sampling at the drilling sites is also being followed up here.

- The formation and transport of colloids is being studied at the Department of Nuclear Chemistry at Chalmers University of Technology.

- Complex formation with humus substances is being studied at New York State University in Buffalo.

- The sorption of actinides and technetium, as well as associated equilibria, are being studied at the Department of Nuclear Chemistry at Chalmers University of Technology.

- Laboratory measurements of retardation in fractures and measurements of diffusion in rock samples and on mineral surfaces are being performed at the Department of Chemical Engineering at the Royal Institute of Technology.

- Geological evidence for diffusion into the rock matrix is being sought in connection with the studies of uranium mobility being carried out at the Geological Survey of Sweden in Luleå. Experiments are also being conducted to determine chloride diffusion around saltwater-bearing fractures (the Geological Survey of Sweden, Gothenburg, and the Department of Chemical Engineering at the Royal Institute of Technology).

- In-situ studies of radionuclide migration in fissured rock are being conducted at Studsvik.

- In-situ tests aimed at determining the porosity and thereby the capacity for volumetric sorption of undisturbed rock are being conducted at Stripa by the Department of Chemical Engineering at the Royal Institute of Technology.

- A mathematical model to describe the geosphere transport of nuclides with groundwater is being developed at the Department of Chemical Engineering at the Royal Institute of Technology. The model includes, among other things, matrix sorption in the rock and dispersion.

4.4.3 Geological stability

The Swedish Precambrian bedrock belongs to the Baltic Shield and consists of crystalline rock. The Baltic Shield is regarded as one of the most stable regions in the earth's crust. However, local fracture movements and regional land uplift have occurred even after the Precambrian mountain ranges were eroded down some 600 million years ago. There are no signs to indicate that extensive movements in the bedrock will take place during the next few million years, but the risk that stress conditions in the bedrock may give rise to local fracture movements cannot be ruled out entirely.

Stress redistributions and movements in the bedrock can give rise to earthquakes. With access to data from seismometer recordings, the mechanism of an earthquake can be analyzed in terms of the magnitude, direction and location of the movement.

The purpose of the studies of the stability of the crystalline rock is to predict future changes and their effects on the repository and the groundwater flow.

In many cases, it has been found that earthquakes are followed by aftershocks, which are considered to be of the same type as the main quake. By installing mobile seismometers in the area surrounding the observed epicentre of an earthquake, it is possible to study the movements in the bedrock in connection with aftershocks in greater detail. This yields data for a quantitative description of how the rock is affected by the ongoing stress redistribution and provides an opportunity to show correlations with zones of tectonic weakness. The current program includes the collection of data from aftershocks for the purpose of interpreting the mechanisms of movement.

A field study has been carried out in which data have been collected on frequencies and displacements of individual fractures on rock outcroppings.

The next five-year period will include research on proven and presumed neotectonic phenomena in Sweden as well as an assessment of the likelihood of fracture movements within the typical areas.

The feasibility of using rock stress measurements and datings of fracture-filling minerals to interpret the tectonic history of an area will be studied.

The investigations of bedrock movements with the aid of seismometry and analysis of aftershocks will continue.

The Geological Survey of Sweden and associated consultants, as well as the Department of Seismology at the University of Uppsala, are currently engaged in this research.

4.4.4 Instruments and methods for data collection

A large portion of the research work on the geosphere is concerned with instruments and methods for data collection.

A great deal of work has been done in recent years by SKBF on the development of instruments and methods for hydrogeological measurements. One of the new instruments that has been developed is used for measuring the hydraulic conductivity of the rock in boreholes. This equipment has now been manufactured and tested and is in routine use for measurements in the study areas. All data is collected on tape and a preliminary processing of the results is carried out directly on the site with the aid of a computer.

Equipment for the chemical sampling of groundwater has been field-tested. The sampling is controlled by changes in pH, Eh, pS^{2-} or pO_2, which are measured continuously and recorded digitally. Work is also being conducted on equipment for measuring these values directly in the borehole in sections sealed off by packers.

Work is in progress on the development of instruments and methods for improved characterization of the structure and properties of the rock mass between accessible points of investigation. The emphasis has been placed on seismic, electrical and electromagnetic methods.

Activities during the coming five-year period will include the continued development of geophysical instruments and methods for cross-hole measurements and measurements between the borehole and the ground surface. A proposal has been drawn up for a program of such development work at Stripa, with efforts concentrated on the continued development of seismic and electromagnetic methods (cf. section 7.2).

Preparations are being made for the development of instruments and methods for rock stress measurements in sloping water-filled holes with a diameter of 56 mm. This work is planned for inclusion in the coming five-year period.

For the development of the instruments and methods, SKBF engages the services of the Geological Survey of Sweden, IPA-Consult, the Swedish National Defence Research Institute, the Department of Rock Mechanics at the University of Luleå and the Department of Inorganic Chemistry at the Royal Institute of Technology.

4.4.5 Methods for sealing of boreholes, tunnels and shafts

The backfilling of spaces in the rock that are not occupied by waste, canisters or buffer constitutes part of the barrier system.

Methods for compacting and sealing materials have long been in use in the civil engineering field. In mining, the filling of excavated spaces has been used for mechanical stabilization, but without any special requirements on a tight seal. An example of a method to improve the imperviousness of fractured rock is injecting cement mortar into boreholes. From the viewpoint of a final repository, methods for permanently sealing holes in the rock are of great interest, and especially methods that reduce the hydraulic conductivity that stems from disturbances in the surface zone of the excavated rock.

Methods for plugging boreholes with cement mixtures are being studied in the United States, mainly for salt and basalt conditions.

Owing to its swelling capacity, highly-compacted bentonite can be used to seal fractures. The backfilling of boreholes with plugs of this material in perforated pipes has been tested both in the laboratory and in the field.

During the next five years, the main emphasis will be on the development of methods to plug tunnels and shafts, particularly sections with open fractures and crush zones. Not only bentonite, but also other materials (e.g. MgO) and material mixtures will be tested.

The R&D program for the next five years includes:

- plugging experiments at Stripa with highly-compacted bentonite (cf. section 7.2),

- laboratory tests of various mixed materials (e.g. bentonite/MgO),

- studies of geological analogies for the self-sealing capacity of swelling materials in bedrock.

The work is being done mainly by the Division of Soil Mechanics at the University of Luleå.

4.4.6 Site investigations

A general timetable for the site investigations is shown in Figure 4-2.

Local geological and hydrological conditions are of decisive importance in the final choice of the site for a final repository. Consequently, before this choice can be made, extensive investigations have to be conducted of a number of potential areas so that the choice can be based on adequate knowledge of several "typical areas". For these investigations, SKBF and SGU (the Geological Survey of Sweden) have drawn up a standard program with the following essential content:

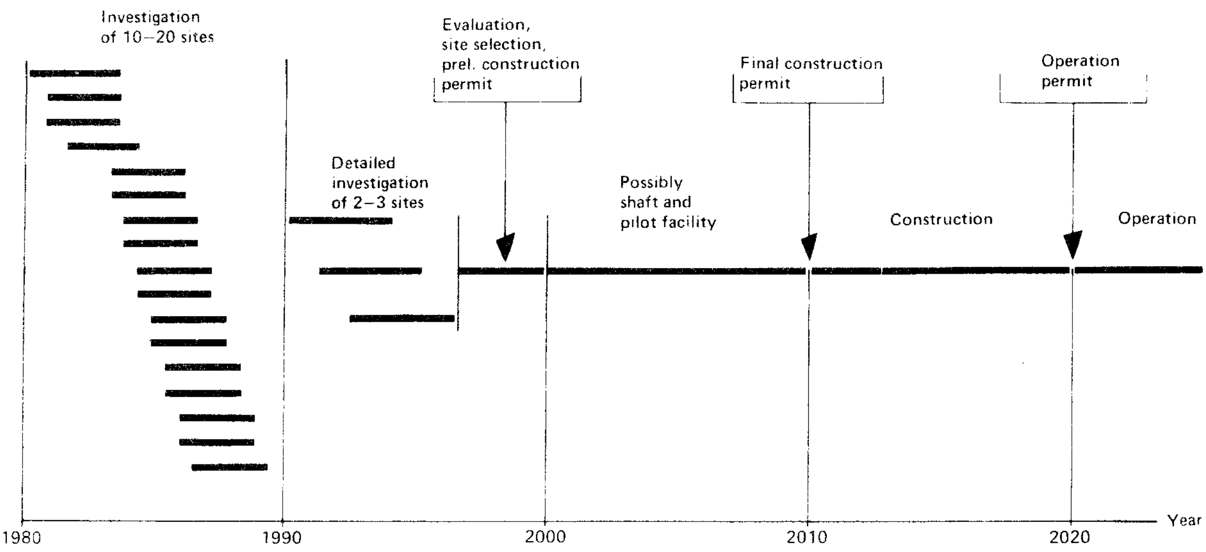

Figure 4-2. General timetable for geological surveys and construction of final repository, SFL.

Stage 1 comprises an initial study of regional conditions within a number of areas with the aid of available geological, geophysical and topographical maps, satellite and aerial photographs, well-logging data, landowner-supplied information etc. These studies lead to the identification of a smaller number of areas of interest, which are therefore subjected to general field reconnaissance.

If an area is then still deemed of interest, permission is obtained from the landowner to conduct further investigations and drilling, and an initial deep borehole is drilled. The purpose of the borehole is to show whether the area offers suitable rock conditions at greater depth well before proceeding to subsequent, more time-consuming and costly investigations.

Stage 2 consists mainly of detailed geological and geophysical surface investigations aimed at determining the principal hydrogeological features of the area and collecting data as a basis for the planning and orientation of the coming depth investigations.

At this stage, an attempt is made to distinguish the existing major sections of sound rock from the surface and to map the zones of disturbance that might influence the groundwater movements and the space available for a repository.

Surface investigations are then followed by hammer-drilled holes to a depth of 100-200 m. These holes are used to investigate the character of the surface-indicated zones of disturbance, their slope and any interconnections between them.

This stage also includes investigations of the larger zones of disturbance that consitute the hydrological boundaries of the study area. Pumping in boreholes directed through such zones and measurement of the lowering of the groundwater table in surrounding observation holes can yield information on water both in the zone of disturbance and in surrounding sections of sound rock.

Geological interpretation of the results of this stage provides an initial picture of the probable location of the zones of disturbance at greater depth and of the extent of sound rock between them. The subsequent depth investigations are then planned on the basis of these results.

In Stage 3, the distribution and properties of the sound rock and zones of disturbance at greater depth are investigated. This is done in a limited number of deep core boreholes drilled down to and beyond the proposed depth of the repository. The holes provide an opportunity for sampling the rock and its fracture zones and for geophysical and hydraulic measurements. Sampling and analysis of the groundwater from sealed-off sections clarifies on the chemical conditions around a planned repository.

In Stage 4, the data obtained is compiled and evaluated.

The measurements provide the input data needed for a calculation of the groundwater movements in the area.

During the evaluation stage, it may prove desirable to carry out certain supplementary field surveys in order to fill gaps in earlier observation material.

The Finnsjö Lake, Kråkemåla and Sternö areas have already been investigated. At present, investigations are being conducted in the municipalities of Ovanåker, Nyköping, Örnsköldsvik and Kalix.

Studies carried out to date have been almost exclusively concerned with rocks of granitic composition. According to preliminary assessments, other rock species, for example gabbros and the ultramafites found in the Swedish mountains, may be able to meet the requirements imposed on a surrounding rock barrier. These rock types will be studied.

As shown in Figure 4-2, it is intended that 10 to 20 areas representing different rock types should be studied by means of the standard program described above. The collected material will be subjected to an evaluation around the year 1990, whereby 2-3 of these areas will be selected for more detailed studies. Final selection of the area for a waste repository will then be made during the mid-1990s. This will leave time for driving a shaft down to the repository level to verify the quality of the rock, as well as the construction of a pilot plant, if desired.

4.5 BIOSPHERE

4.5.1 Global and regional dispersal

Knowledge concerning the dispersal of radioactive substances in the biosphere is required for calculating dose burdens from releases of radionuclides into different biosphere recipients. This knowledge also helps to provide a qualitative understanding of the importance of the various transmission links in the dispersal process and the consequences of changes in these links.

Dispersal in the biosphere can be described on two levels:

Regional dispersal defines the concentrations of radionuclides in those parts of the biosphere that give rise to the maximum individual doses. At this level, dispersal is often dominated by conditions in the initial recipient and its use by man.

Global dispersal is controlled to a great extent by large-scale transport in the global oceans, sedimentation conditions in the oceans and global distribution between a biologically accessible and an inaccessible fraction of the various substances.

Since the Swedish radiation protection standards aim at restricting both the individual dose and the total population dose from waste management both dispersal levels must be studied.

A number of mathematical models are available for calculating dispersal in the biosphere. SKBF is currently using a model developed by Studsvik Energiteknik (BIOPATH). An international comparative evaluation of biosphere models is currently being conducted under the auspices of the IAEA.

The international literature contains a large quantity of nuclide-specific data on transfer factors between different reservoirs in the biosphere. There is considerable scatter in the data, however, resulting in a large degree of uncertainty in the calculations.

International activities in this field will be covered. Samples will be taken in areas of interest within the country. These efforts will be focused on isotopes that dominate the risk picture for the repository designs currently being considered and to environments that are characteristic of Swedish conditions.

At present, Studsvik Energiteknik is doing most of this work, together with the Swedish College of Agriculture in Ultuna and SGU (The Geological Survey of Sweden).

4.5.2 Site-specific conditions

Much of the uncertainty in our data on transfer factors in the biosphere stems from differences in environmental conditions from place to place. If these site-specific effects could be isolated, their importance for dispersal in the biosphere could be assessed.

At present, only limited efforts have been made within this field in Sweden. However, a large body of basic data has been collected by the Swedish Environment Protection Board concerning e.g. the mobility of heavy metals in Swedish lakes. Certain site-specific information concerning the transport of naturally-occurring radioactive substances has also been obtained from uranium prospecting.

Additional work will be concerned with isotopes that are of interest for a final repository and areas in which site investigations will be performed (see section 4.4.6).

Some of the information will be obtained during the site investigations, and the work is planned to be carried out in two stages. The first stage is expected to be completed by the end of 1988.

A second stage will be completed by 1995, involving further studies including the sampling of certain chemically or geologically special recipients for the purpose of gaining further knowledge of the range of important parameters.

4.5.3 Long-term changes

Owing to the long travel times of the radionuclides through the geosphere, the consequences in the biosphere from a final repository for radioactive waste may become manifest only after very long periods of time, probably longer than those during which man has existed as a separate species.

Environmental changes of importance for the safety assessment occur on different time scales:

Time scale	Changes
10^2 years	Changes in recipients, such as the eutrophication of lakes etc.
10^4 years	Climatic changes such as ice ages etc.
10^6 years	Evolutionary changes such as the emergence of new species etc.
10^8 years	Geological changes such as the formation of mountain ranges etc.

Certain analyses of the scale and nature of such changes are necessary to be able to evaluate the results of the safety assessment and the degree of detail which is meaningful.

These analyses should be concentrated on changes within the time scale of 10^4-10^6 years, when the effects of climate evolutionary changes will dominate the picture. Changes within shorter time spans will be taken into consideration by assuming unfavourable local conditions for the dispersal of substances that have leaked from the repository.

In view of the high stability of the Baltic Shield, little credence can be given to the possibility of major geological changes having a significant effect on the dispersal of radioactive substances in the biosphere.

A description of the changes caused by an ice age should focus primarily on the periods immediately preceeding and following the ice age, when climatic conditions permit a settled population. The description should deal with the range of possible changes and those natural geographical phenomena that can be expected to be immutable.

Evolutionary changes may be illustrated by the range of variation in the present-day ecosystem on earth.

This field of research is governed to a great extent by how the system of standards and criteria for final disposal of radioactive waste is constructed and how this system will judge the importance of possible effects in a distant future.

Only efforts on a smaller scale appear to be meaningful for SKBF in the present situation to shed light on the importance of long-term changes.

4.5.4 Natural radioactivity

As has become evident from other subsections under 4.5, the long time perspectives constitute a source of considerable uncertainty as regards dispersal of radionuclides in the biosphere. Since mankind may also undergo change, currently accepted guidelines and standards would appear to constitute a too unstable basis for the long-range assessment of acceptability. The only basis for comparison that can be assumed to have any degree of long-range stability is the concentration of naturally-occurring radioactive substances in the biological system and the bedrock. A fundamental principle of acceptance might be that a final repository must not alter the radioactive conditions in its surroundings to any appreciable extent, even over extremely long periods of time. Such an acceptance criterion is largely independent of ecological changes and future permissibility assessments.

A large body of data on the presence of radioactive substances in nature has been collected by SSI (The Swedish National Institute of Radiation Protection) and SGU, among others.

Sampling of groundwater and certain biosphere reservoirs will be carried out at every investigation site during the 1980s. This sampling will be coordinated with the sampling performed in order to determine differences in site-specific conditions as described in 4.5.2.

Attempts will be made to verify the calculations of dispersal in the geosphere and biosphere through studies of natural analogies. It should be possible for large projects of this type to be carried out as joint international cooperative efforts.

4.6 METHODS FOR SAFETY ANALYSIS

This section deals with the need for development work aimed at evaluating overall safety during both the operating and storage phases. The two phases are dealt with separately, since the operating phase involves a safety analysis of active systems with opportunities for monitoring and corrective measures, while the storage phase involves an analysis of a passive system where the primary uncertainty exists in the assumptions regarding external conditions.

4.6.1 Handling, conditioning and transportation

The safety analysis constitutes a systematic description of radiological safety in the normal handling chain, the probability of release of radioactive substances and the radiological consequences of such releases.

The assessment of the safe handling of radioactive substances is carried out in accordance with the guidelines and standards established by the responsible authorities and the recommendations of international organizations.

Methods for the safety analysis of radiological work have been developed in the nuclear power industry so that they can be applied today on a routine basis for permissibility assessments of the various activities. Methods of waste handling are, in large measures, similar in nature, although certain materials and environments have not been tested.

4.6.2 Storage phase

The principal difficulty involved in evaluating the safety of a long-term storage system lies in the wide variety of possible changes in the surroundings and in interpreting the effects of these changes on the waste system. By selecting materials and environments whose long-term properties can be confirmed by reference to geological evidence, it is possible to make a general and long-range characterization of a storage system in terms of storage safety. The value of safety assessments on a time scale of millions of years can, however, be questioned.

Safety analyses are normally performed in two steps:

a) Selection and characterization of the processes or events to be considered (scenario analysis)

b) Estimation of the consequences of the scenario for the environment (consequence analysis).

Some special questions that arise in connection with the safety assessment are:

- How should risks that arise at different times be weighed against each other? For example, how should a handling procedure that causes higher occupational doses today be evaluated against the advantage of perhaps gaining 10 000 years in canister life by using the method?

- How should dose contributions from very long-lived substances be evaluated? This applies in particular to the radioactive substances present in uranium ore, regardless of whether the ore is used in reactor fuel or is allowed to remain in the ground as ore.

Questions of this type should be explored in international collaboration and in close contact with public authorities responsible for safety. Work is currently being done in these areas by the IAEA and the OECD/NEA. SKBF will follow and participate in this work.

4.7 SYSTEM DESIGN

4.7.1 General

As will have become evident from the above, alternative designs of the components that constitute the final repositories are possible within the given frames. Conceptually different designs of the final storage system are also possible.

As regards the low- and medium-level long-lived waste from reprocessing, it has been assumed up to now that it will be stored in conjunction with the high-level waste. The detailed design of the final repository will depend on the chemical composition of the low- and medium-level waste. According to current plans, specifications for this waste are to be submitted by Cogema in a first edition during 1982/83. More detailed studies of a suitable final repository design will then be begun.

As regards the final repository for high-level waste or spent fuel, possible design alternatives are illustrated below.

4.7.2 Geometric design

The following different typical geometric designs of a final repository for high-level waste or spent fuel in crystalline rock have been discussed, see Figure 4-3.

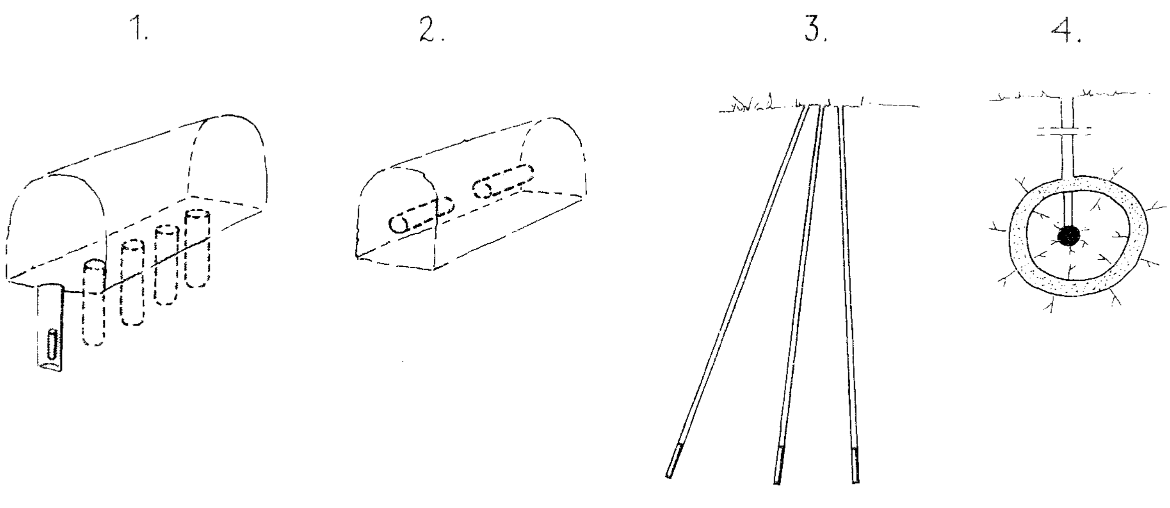

Figure 4-3. Possible designs for a final repository.

1. Disposal of the waste in shallow boreholes drilled in tunnels excavated at great depth.

2. Disposal of the waste in tunnels excavated at great depth.

3. Disposal of the waste in very deep boreholes drilled from the surface of the ground.

4. Disposal of the waste in an isolated body of rock which is sealed off from its surroundings by an impervious material.

The studies carried out thus far in Sweden, as well as a large number of foreign studies, have been based on a geometry in accordance with Alternative 1 above. This design has been deemed to offer the following advantages:

- If an individual canister should leak, the chemical ambient conditions could be worsened as a result of radiolysis. Because the canisters are separated from each other in different boreholes, the risk that such an event will lead to damages to nearby canisters is reduced.

- Since each individual borehole can be examined for fractures and water seepage prior to a decision being made as to whether it should be used for waste disposal, it is possible to ensure that the near field around each canister is of satisfactory quality.

A variant of Alternative 1, where the repository is divided into two or more levels, will be studied, as will the effect of locating the repository at different depths.

A large portion of the investigations being conducted as a part of SKBF's program are applicable to all of the typical designs described above. No special additional investigations are considered necessary for Alternative 2. Alternative 3 requires extensive development of the investigation method. Such development is being conducted abroad, primarily in Switzerland.

A general evaluation of a variant of Alternative 4 (WP cave) has been conducted at SKBF. It was found that the method:

- bases its long-term safety entirely on one artificial barrier consisting of a layer of clay in an excavated slot hole around the repository;

- results in very high temperatures over long periods of time;

- is technically complicated. In addition, the long-term behaviour of the excavated rock and of the concrete structures is difficult to assess.

Since the method does not appear to be superior to other methods from the cost-benefit point of view either, SKBF does not intend to study this type of design any further for the time being.

4.7.3 Temperatures, barriers, groundwater

Different alternatives for the geometric design of the final repository have been described above. Other variations are also conceivable. Thus, it is possible to consider:

- permitting higher temperatures in the repository,
- varying the barrier functions of the canister and the buffer,
- locating and designing the repository in such a manner that transport of radionuclides by the groundwater is prevented.

It is possible to limit the size, and thereby the cost, of the repository by permitting high temperatures. Foreign design concepts often allow higher temperatures. The reasons for the relatively low temperatures (< 100 °C) in the Swedish concept are discussed in section 4.1. In the continued work, consideration will also be given to the effects of higher temperatures.

In the Swedish design concepts, the canister has been assigned the function of first providing total isolation for a very long period of time and later distributing, together with the buffer material, the releases of radioactive substances in time.

One of the tasks in the coming studies will be to evaluate the importance of each barrier and to study the possibilities of reducing or redistributing the functions of the barriers. In this way, the different changes in the dimensions of the buffer and the canister can be weighed against each other at the same time as the repository depth is varied. These studies should be coordinated chronologically with the evaluation of the site investigations scheduled for the late 1980s.

In order to prevent the groundwater transport of radionuclides from the repository, either the repository must be located in an area free of groundwater or special measures must be taken to prevent groundwater flow. Such measures may consist of either surrounding the repository with a watertight shield (as in Alternative 4) or draining the area. Drainage systems only achieve their full effect if they succeed in keeping the repository dry. Otherwise, the drainage system will merely level the hydraulic gradient over the repository area (the "hydraulic cage" described in the commentary on the KBS 2 report submitted by the Royal Institute of Technology), which is also advantageous from the viewpoint of safety.

However, in order for the system to be credited in the safety assessment, with a complete sealing or draining function this function must persist over very long periods of time. It would appear to be difficult to supply evidence of such long-term function today.

5 DECOMMISSIONING OF FACILITIES

5.1 GENERAL

When the nuclear power plants, intermediate storage facilities and treatment plants have been taken out of service, they are to be decommissioned and dismantled and the sites restored so that they can be used without radiological restrictions. Since the facilities contain large quantities of safety materials that are contaminated by radioactivity, special requirements are made on the manner in which the decommissioning is carried out.

A number of studies have been conducted in other countries of how nuclear facilities are to be dismantled. KBS TR 79-21 gives an account of how a Swedish BWR can be dismantled. The conclusion reached in this study, as well as in other studies, is that it is quite feasible to decommission and dismantle a nuclear power plant using currently available technology. The methods proposed are already used on a large scale in maintenance work on the reactor plants. However, methods that have only been tested in an inactive environment are proposed for dismantling certain parts, for example the reactor vessel.

Considerable quantities of waste are obtained in connection with dismantling. This waste is of such a character that it is not expected to give rise to any new problems from the viewpoint of final storage. It is planned that decommissioning waste will be deposited in the SFR.

5.2 DECOMMISSIONING IN OTHER COUNTRIES

A number of nuclear power plants have already been taken out of service in various parts of the world, for example Lingen and Gundremmingen in the Federal Republic of Germany, Shippingport in the United States etc. Over the next 10 years, this number will increase. It can be expected that some of them will be dismantled relatively soon after shutdown, while others will be mothballed following decontamination.

This means that considerable experience will be acquired from the practical procedures in connection with decontamination and dismantlement. In this context, the decontamination of TMI-2 may also be expected to provide valuable information.

In parallel with the actual dismantling work, a development of methods to simplify the work of decontamination and decommissioning is expected to take place. Such development work is being planned within the frame of the OECD and EEC programs as well as in France, Federal Republic of Germany and the United States.

5.3 PLANNING

Over the next five-year period, efforts will be concentrated on following up development work all over the world. With these findings as a basis, a new comprehensive decommissioning study will be conducted towards the end of the period.

In conjunction with major repair and maintenance work on the Swedish nuclear power plants, competence will be built up within the nuclear power companies within areas that are of importance for decommissioning. Examples of such areas are decontamination methods, reconstruction work in a radioactive environment and management of the waste.

In the longer term, 5-10 years before the first nuclear power plant is to be decommissioned, work should be commenced on a method development aimed directly at application in connection with the decommissioning of the Swedish nuclear power plants. The Ågesta reactor may then be used for practical tests of decommissioning methods in a manner similar to that now being planned for decontamination.

A large portion of the waste obtained in connection with nuclear power plant dismantlement is virtually inactive. It is therefore important, in order to restrict the quantity of waste that will have to be disposed of as radioactive waste, that rules and methods of measurement be established for exempting such waste as non-radioactive. Responsibility for this rests primarily with the safety authorities.

6 REUSE OF URANIUM AND PLUTONIUM AFTER REPROCESSING

6.1 GENERAL

When it is discharged from the reactor, the spent fuel contains three main constituents:

96% uranium
1% plutonium
3% fission products and other transuranic elements

The fuel is separated into these three constituents by reprocessing. The fission products and other transuranic elements constitute the high-level waste, while uranium and plutonium are obtained in such a pure form that they can be reused as fuel. The Swedish power industry has signed contracts with BNFL and Cogema for the reprocessing of a total of 67 tonnes of uranium, whereby just over 6 tonnes of plutonium will be obtained. The uranium's content of the fissionable isotope 235 is slightly higher than the concentration found in natural uranium. The plutonium consists of about 67% of the fissionable isotopes 239 and 241.

6.2 USE OF URANIUM AND PLUTONIUM

Uranium obtained from reprocessing can be re-enriched and used as fuel in Swedish reactors. It meets the requirements on purity stipulated in the enrichment contracts without any pretreatment. The uranium from reprocessing takes the place of a roughly equivalent quantity of natural uranium.

As regards the plutonium, there are two possible areas of application: as fuel in a breeder reactor or in a light water reactor. In Sweden, only the light water reactor alternative is realistic.

6.3 SITUATION AS REGARDS REUSE OF PLUTONIUM IN LIGHT WATER REACTORS

Plutonium-enriched fuel, known as MOX fuel, has been used on trial in light water reactors in different parts of the world for about 15 years. Three elements have been tested at Oskarshamn 1. The greatest experience concerning both the fabrication and the use of plutonium-enriched light water fuel is to be found in the Federal Republic of Germany, where a total of more than 200 fuel elements have been used with good results.

A study of how plutonium recovered from the reprocessing of Swedish fuel can be reused in the Swedish reactors is currently being conducted by SKBF. A report on its results can be expected during the autumn of 192. A preliminary conclusion that can be drawn already from this study is that no technical obstacles exist to such a reuse.

6.4 ACTIVITY PLAN

The continued work of preparing for the reuse of plutonium will be carried out for the most part by the power utilities. This work will involve studies required for the licencing of the reactors that are to use plutonium-enriched fuel as well as optimization of the fuel design.

The earliest possible time at which plutonium elements can be used on a regular basis is towards the end of the 190s, when the reprocessing of Swedish fuel commences at Cogema in La Hague.

7 INTERNATIONAL COOPERATION

7.1 GENERAL

There is widespread international cooperation and exchange of information within the field of research and development aimed at ensuring a safe disposal of radioactive waste. International information exchange takes place on different levels:

- Within official organizations such as the IAEA and the OECD/NEA.
- Through bilateral or multilateral agreements.
- Through international symposiums and conferences arranged by different organizations.
- Through international consulting assignments and informal direct contacts between experts or groups of experts from different countries.

International cooperation is of great importance in two respects:

- The total fund of available resources and know-how can be better utilized.
- It affords opportunities for a desirable international coordination of regulations and acceptance criteria.

From Sweden, the supervisory authorities of SKI and SSI, Studsvik, PRAV and SKBF have participated in the international work within the IAEA and the OECD/NEA. Representatives of SSI have especially participated in the work within the ICRP.

SKBF has signed bilateral agreements for an exchange of information with the US Department of Energy (DOE), Atomic Energy of Canada Ltd (AECL) and the Swiss Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (NAGRA). Within the framework of these agreements, there is a continuous exchange of reports and regular meetings for mutual information. In some cases, these meetings have led to more concrete cooperation between the specialists attached to the parties. The agreements also paved the way for jointly financed projects and an interchange of qualified personnel.

An exchange of information without formal agreements also takes place between SKBF and organizations in Finland, France, Japan and West Germany as well as with the EEC's group in charge of waste questions.

Numerous international meetings, committees etc. are organized within the IAEA and the OECD/NEA as well as other independent organizations. The scope of these activities is so large today that it is impossible for SKBF to keep up with all of them. The Swedish organizations that have a particular interest in participating in such activities are, besides SKBF and its joint owners, NAK, SKI and SSI. A greater degree of coordination and a clearer assignment of roles between these different Swedish organizations would be desirable in order to permit the greatest possible benefit to be extracted from the information available internationally.

7.2 THE STRIPA PROJECT

Work is currently in progress under the management of KBS on an international cooperative project in the Stripa mine located in the Bergslagen district of central Sweden. The project, which is an independent OECD/NEA project, involves research on the storage of radioactive waste from nuclear power plants in crystalline bedrock. Besides Sweden, the countries participating in the project are Finland, France, Japan, Canada, Switzerland and the United States. The project consists of three independent subprojects:

- Hydrological and geochemical investigations in deep boreholes
- Migration tests in an individual fracture
- Investigations of buffer and backfill materials in a simulated repository environment.

The project, which started in May of 190, is scheduled to be concluded in May of 194. The total cost is estimated at about SEK 50 million.

Considerable interest has been shown by both the OECD/NEA and the current member countries in a continuation of the Stripa Project into a second phase. Studies are currently being discussed under the following headings:

- Cross-hole techniques for the detection and characterization of fracture zones in the vicinity of a repository.
- A 3-dimensional tracer experiment.
- Borehole and shaft plugging tests.
- Diffusion tests in buffer materials.

This second phase is planned to start in January 193 and be completed during 196. The cost frame being discussed is approximately SEK 65 million.

7.3 THE JSS PROJECT

The JSS project is a joint Japanese-Swedish-Swiss project for examining the resistance of radioactive glass in a geological environment. The radioactive glass, which has the same composition as the proposed glass from UP 3 in La Hague, is being made available to the project by Cogema. The experiments will be carried out by Studsvik and by EIR, Switzerland. The project is under the management of KBS and will be carried out during the period 1982-1984. The cost - which is being shared equally between CRIEPI, Japan, NAGRA, Switzerland and SKBF - is estimated at SEK 7 million for the entire project period.

8 TIMETABLES

The waste activities within SKBF are aimed at a safe handling and final storage of radioactive residues from nuclear energy production and the decommissioning and dismantling of the nuclear facilities.

The planning is based on the assumption that the necessary technology and required systems and facilities will be available at the right time in order to permit implementation of:

- handling
- transportation
- intermediate storage
- conditioning
- final storage of waste products

The time frame is determined by the Swedish nuclear power program, contracts for the reprocessing of spent fuel and a 40-year period for waste decay prior to deposition in a final repository not earlier than the year 2020.

The various activities can be grouped under the following main headings:

- engineering and construction of systems and facilities

- operation of systems and facilities

- research, development and investigations for selection of methods, design and siting and for safety assessments.

The timetables for the first two groups are dictated by the deadlines stipulated in Chapter 2 and by the lengths of time shown by experience to be required for planning and design, licencing and construction. The research, development and investigatory work must, however, be scheduled in a more flexible manner.

The work shall be carried out in such a way that:

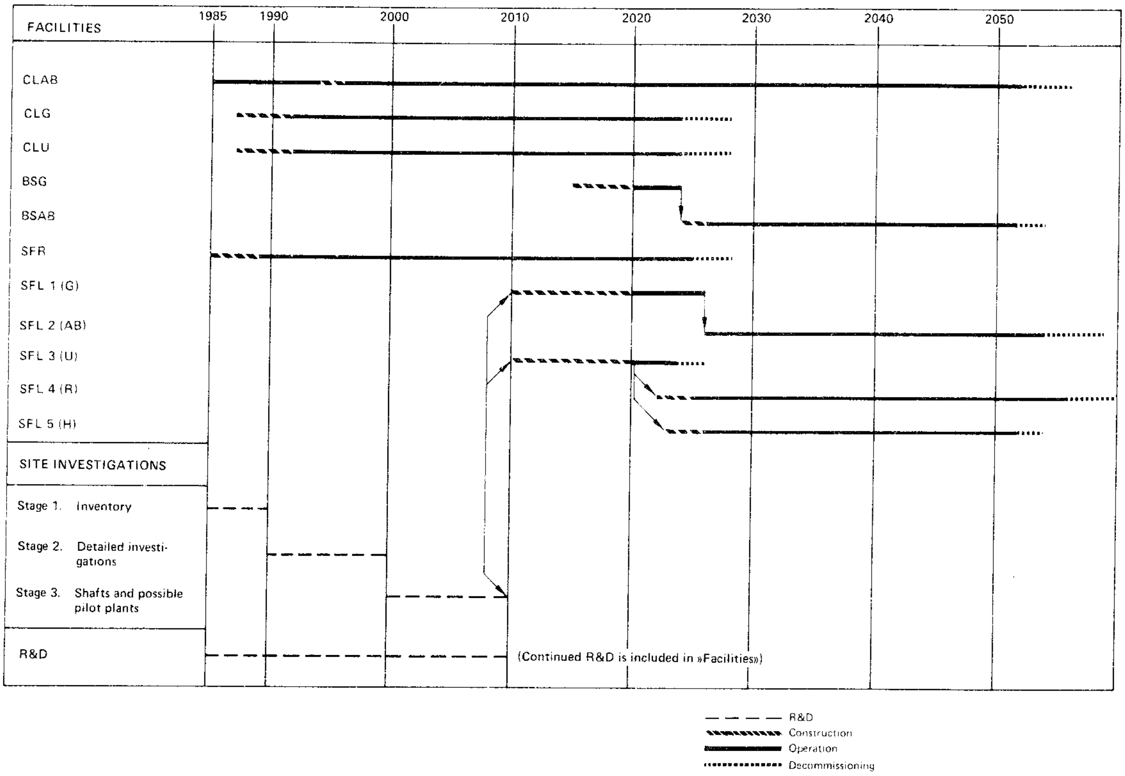

Figure 8-1. Overall timetable for SKBF's waste management activities

- a sufficiently broad overview is obtained as a basis for determining the direction of continued activities;

- a sufficiently detailed body of information is collected in order to permit evaluation of alternative designs of systems and facilities;

- an adequate basis is obtained for planning, designing and constructing facilities and systems and for establishing the necessary requirements on quality and control;

- an adequate basis is obtained for the safety-related assessments that are required for licence applications.

The scope and direction of this work is determined to a great extent by the results that are continuously being obtained and the evaluations that are continuously being made. In the timetables shown in Figures 8-1 and 8-2, R&D and investigatory work, the scope and importance of which may vary considerably, has been indicated schematically with dashed lines.

The long-term plan shown in Figure 8-1 is based on the assumptions that it will be possible to seal the facilities for final storage of reactor waste shortly after the nuclear reactors have been taken out of operation and that the final disposal of spent fuel or high-level waste will commence in the year 2020 and continue

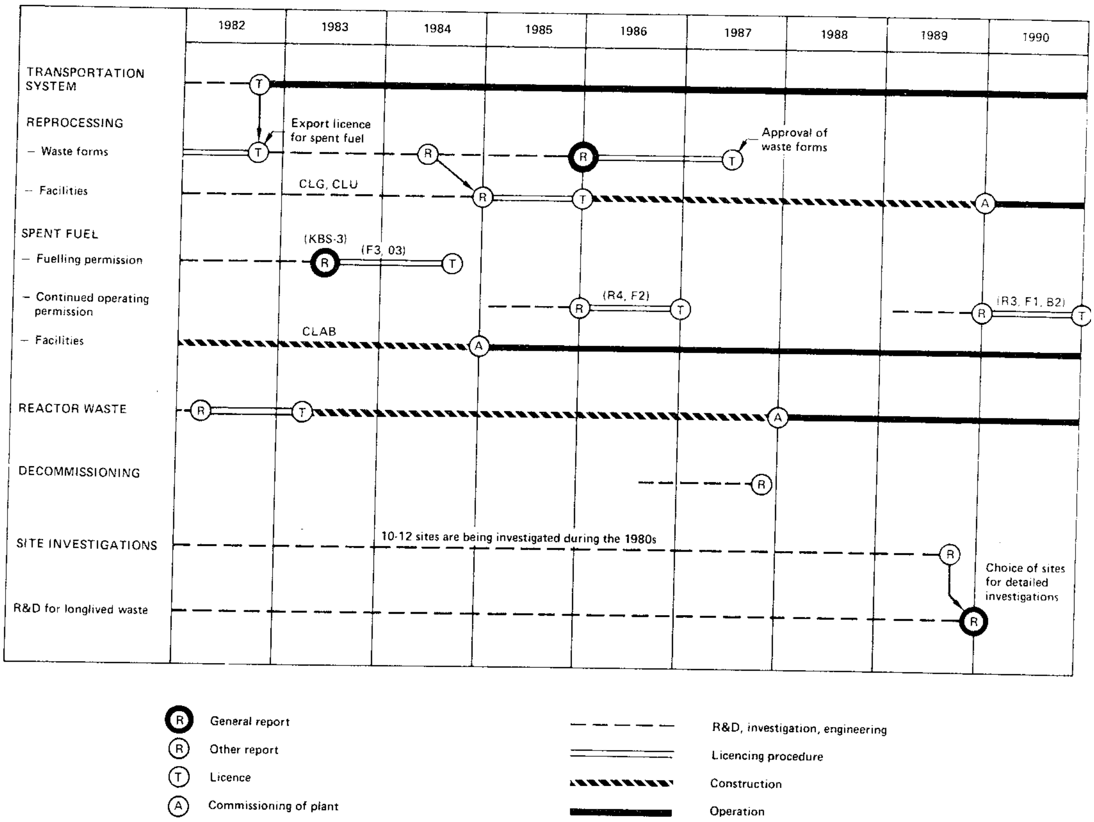

Figure 8-2. SKBF's planned waste management activities, 1982-1990

at a regular pace for a period of 30 years. All the facilities are planned to be decommissioned and dismantled when they have fulfilled their functions.

The plan for the period 1982-1990 is shown in Figure 8-2. As regards the reprocessing waste, the work is governed by the times set for the transportation of fuel and for reprocessing and by the time scheduled for the return of waste from reprocessing.

As regards spent fuel, the work is currently being concentrated on the preparation of an account of how and where a safe final storage can be effected. This report is planned to be submitted to the Government during the first half of 1983 in support of fuelling applications for the F3 and O3 reactors under the terms of the Stipulation Act. The report will comprise a compilation and application of current knowledge and is expected to provide, together with expected commentaries on the proposals, a sound basis for continued R&D work.

The operating licences for certain reactors are limited as to time. Thus, new licences will be required for the R4 and F2 reactors by no later than the end of 1986, and for the R3 and F1 reactors before the end of 1990. The applications for continued operation of these reactors must be accompanied by updated reports on the handling and final storage of the waste.

With regard to the decommissioning and dismantling of nuclear power plants, the intention is to follow international developments during the next few years and to prepare a new situation report in about five years.

9 COST ESTIMATES

The estimated costs of the activities aimed at a safe disposal of the radioactive waste from Swedish nuclear power plants are reported in part 2 of this report "Facilities and costs". A summary of some of the most important items in this report is given below.

9.1 PREMISES

The timetable for the various activities and procurements is based on the information provided in section 2.1.

As regards the quantities and types of waste, the cost estimates are based on the information furnished in section 2.2.

As has been pointed out in the preceding sections of this report, it has not yet been determined in detail today how the different categories of waste are to be handled, treated and finally disposed of. This applies in particular to the treatment and final storage of the long-lived waste. Therefore, one scenario, which is considered to be plausible and technically feasible, has been defined for the purpose of the cost estimates. This scenario is described in part 2 of this report.

In those cases where the final premises are unclear, assumptions have been made that cannot reasonably be expected to lead to an underestimation of the costs. An example of this is the assumption that the final repository for long-lived waste - the site of which is not expected to be established until about the year 2000 - will be located approximately 150 km from the coast and approximately 600 km north of Stockholm. It must be emphasized that this assumption has only been made in order to provide a basis for the cost estimates and is in no way associated with any judgement as to the particular suitability of that location with regard to geological and other aspects.

As regards R&D work, it has been assumed that the level of R&D efforts will be largely the same up to the year 2010 as it is now. After 2010, it is assumed that the development costs will be assigned to the different facilities. A special cost of SEK 500 million has been estimated for possible test shafts and pilot plants.

No special cost entry has been included for surveillance of the sealed repositories. If such surveillance should prove necessary, it is assumed that its cost would be negligible in comparison with the total cost. The same applies to the marginal cost for NAK's operation.

9.2 PERFORMANCE OF COST ESTIMATES

With regard to contruction costs, the total costs have been broken down as follows:

Basic costs

A. Costs for materials and labour
B. Joint costs (general site costs and overheads, 48-61% of A)
C. Contractors' fees (10%).

Adjustments
D. For lack of detail in basic data (10-40% of A+B+C)
E. For contingencies (10 or 25% of A+B+C+D)

The construction costs have been based on drawings and data on quantities. The degree of detail in this material varies from facility to facility and even from one part of a facility to another. In order to compensate for the lack of detail in the basic data available, certain uncertainty factors have been applied. In the case of carefully studied facilities, an adjustment of 10% has been applied, whereas an adjustment of 40% has been applied for facilities where the degree of uncertainty is greatest. In addition, a general adjustment of 10 or 25% has been added for contingencies, depending upon how far the engineering or construction has progressed.

The basic costs are based primarily on experience gained from the construction of the CLAB and Oskarshamn 3.

The costs for process equipment have been broken down as follows:

Basic cost

A. Materials and erection
B. Additional cost for procurement and inspection (15%)
C. Site costs (15% of A+B)

Adjustments

D. For lack of detail in basic data (20% of A+B+C)
E. For contingencies (10% of A+B+C+D)

This means that for the entire system, i.e. both buildings and process equipment, an average adjustment to the basic cost of 25% is applied.

SKBF's central costs (5-7% of the total initial capital expenditure) and building engineering costs (4-9% of the construction cost) must then be added to the sum of the initial capital expenditure costs given above.

It has been assumed that certain parts of the facilities will be subject to wear and tear and will have to be replaced during their operational lifetime. Such reinvestments have been estimated at 3-25% of the original investment.

The operating costs for the facilities have been estimated in each individual case.

The costs of decommissioning the power plants are based on KBS Technical Report No. 79-21 after index adjustment of the cost data given therein.

The reprocessing costs have been set at SEK 2 750 - 3 500 per kg of uranium in the spent fuel. The value of recovered uranium has been set at SEK 400/kg. Recovered plutonium has not been assigned any value.

A computer-based system has been developed for compiling and analyzing the cost data. This system can rapidly retrieve information on partial costs in different groupings and clarify the effects of different variations in the premises.

The reported costs are tied to the price level prevailing in January of 1981. The price level at the beginning of 1982 is roughly 10% higher.

9.3 RESULTS OF COST ESTIMATES

After deductions have been made for those costs to which the provisions of the Financing Act do not apply (reactor waste and waste not associated with nuclear power, for a total of approximately SEK 1 500 million), the total cost of the entire system, including operation and sealing of the facilities and decommissioning of the nuclear power stations, is estimated at approximately SEK 29 000 million (January 1981 price level) up to the year 2060, when, according to the existing plan, all final repositories will have been sealed. In the long-term program that has been described, the possibility cannot be ruled out that unforeseen factors will affect the costs. It has therefore been deemed prudent at this stage to adjust the cost upwards by SEK 3 000 million, over and above the adjustments for contingencies included in the basic cost estimate. This would bring the total cost up to SEK 32 000 million, in January 1981 prices. The scenario that has served as a basis for the cost estimates incorporates considerable safety margins in order to compensate for the limitations in the basic data available at this time. It is expected that it will be possible to reduce these margins as

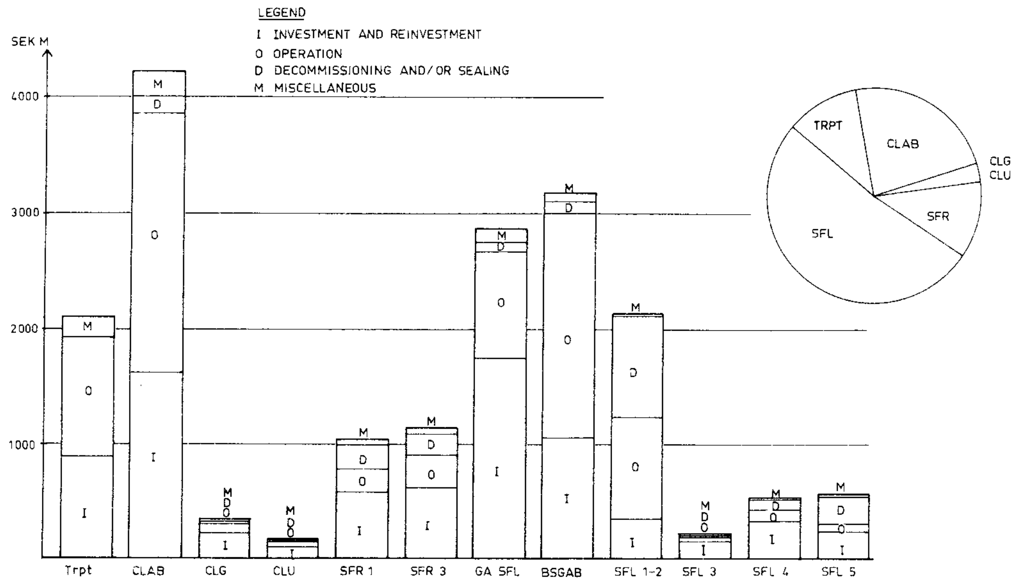

Figure 9-1. Costs per facility (January 1981 price level)

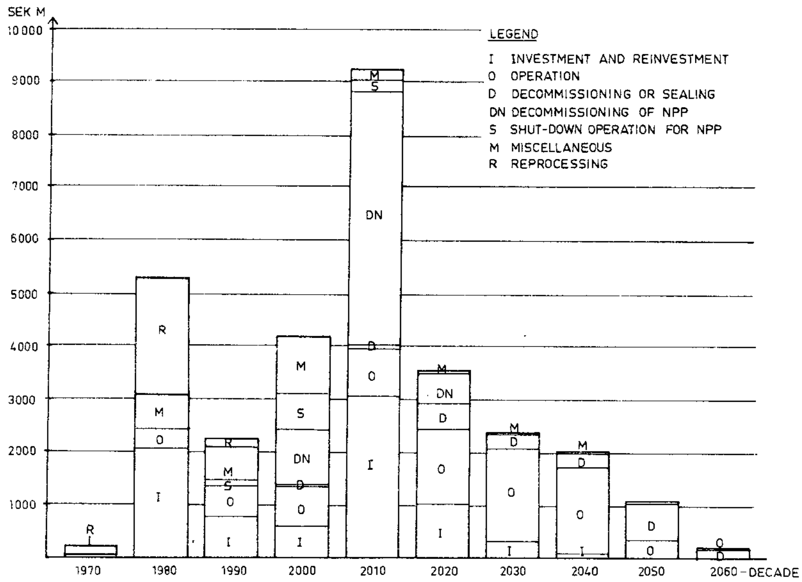

Figure 9-2. Costs distributed in time (January 1981 price level)

the R&D work progresses. The total sum stated, SEK 32 000 million (January 1981), may therefore be regarded as providing adequate coverage for expected costs. During the period January 1981 - January 1982, the cost level has risen by approximately 10%.

The total cost amounts to about 10% of the value of the corresponding electrical power production.

Since facilities and process equipment will be required at different times, the reported costs will fall due at different times. This has not been taken into account in the estimates, but can be taken into account by discounting.

The distribution of the stated costs among different objects is shown in Figure 9-1. (R&D and decommissioning of the nuclear power plants are not included.) The costs are distributed in time as shown in Figure 9-2. Approximately 70% of the total costs will fall due after nuclear power production in Sweden is expected to have terminated.

10 EXTERNAL INFORMATION

During the preliminary drafting work on the Financing Act, special stress was laid on the importance of furnishing frank and complete information to the authorities and to the general public on matters concerning nuclear waste. It is specifically stated that this will be an important task for NAK. Naturally, SKBF is prepared to assist NAK in furnishing such information. In addition, SKBF feels responsible for supplying information to concerned municipalities and county administrations on planned geological investigations before any drilling work commences. The same applies with regard to the planned locations of facilities, such as the SFR. Information of this type is supplied both in writing and at meetings with representatives of the municipalities and the county administrations.

When it is judged to be in the public interest, SKBF prepares and distributes brochures or other publications that describe different aspects of its activities. Short films (Stripa, SFR) and film strips are also included in SKBF's information plans.

The technical information is published in a series of technical reports, of which the final one each year is in the form of an annual report. These reports are distributed to Swedish and foreign organizations and individuals in limited editions. They are also available on microfiche at Studsvik Energiteknik AB's library.

The nuclear power utilities have established a group for the external dissemination of information on radioactive waste. SKBF participates in this work.

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TR 80-26 The KBS Annual Report 1980.
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TR 81-17 The KBS Annual Report 1981.
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Roger Thunvik
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TR 82-02 Radiolysis of groundwater from HLW stored in copper canisters
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TR 82-03 Migration of radionuclides in fissured rock: Some calculated results obtained from a model based on the concept of stratified flow and matrix diffusion
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Stockholm, Sweden, October 1981

TR 82-04 Radionuclide chain migration in fissured rock - The influence of matrix diffusion
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Akke Bengtsson **
Bertil Grundfelt **
Ivars Neretnieks *
April, 1982

* Royal Institute of Technology
Department of Chemical Engineering
Stockholm, Sweden

** KEMAKTA Consultant Company
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Calculation of rock permeability
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Roland Pusch
Division Soil Mechanics, University of Luleå
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TR 82-08 Diffusion in the matrix of granitic rock
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Part 1
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Royal Institute of Technology
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Part 1 General
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TR 82-09:2 Radioactive waste management plan
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TR 82-10 The hydraulic properties of fracture zones and tracer tests with non-reactive elements in Studsvik
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Ove Persson
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