DISPOSAL OF RADIOACTIVE WASTE

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NEA

The Cost of High-Level Waste Disposal in Geological Repositories

An Analysis of Factors Affecting Cost Estimates

NUCLEAR ENERGY AGENCY

OECD
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PARIS

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971) and New Zealand (29th May 1973). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of all European Member countries of OECD as well as Australia, Canada, Japan and the United States. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

- *encouraging harmonization of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
- *assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;*
- *developing exchanges of scientific and technical information particularly through participation in common services;*
- *setting up international research and development programmes and joint undertakings.*

In these and related tasks, NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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LES COUTS DE L'ÉVACUATION DES DÉCHETS HAUTEMENT RADIOACTIFS
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Analyse des facteurs influant sur les estimations des coûts

FOREWORD

This study presents an international review of cost estimates for the disposal in geological repositories of spent fuel or reprocessing wastes (high-level vitrified waste and long-lived alpha-bearing waste from reprocessing). The objective of the study is to provide better understanding of the origins of wide variation of the cost estimates, and to demonstrate to what extent various political, institutional, technical and economical factors could explain the variation. The report is intended for the general reader with an interest in the topic.

The work has been carried out by an international group of experts under the auspices of the Nuclear Energy Agency's Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). The report does not necessarily represent the views of Member governments or participating organisations. The report is published on the responsibility of the Secretary-General of the OECD.

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EXECUTIVE SUMMARY

The disposal of spent fuel or reprocessing wastes (*i.e.* high-level vitrified waste and alpha-bearing waste from reprocessing) in geological repositories has been studied for many years in all OECD countries with a nuclear programme. These studies have demonstrated that safe disposal is feasible in many different types of geological media and that both short-term and long-term safety can be evaluated with acceptable confidence.

Although the actual disposal of such waste is not planned to start in any country until the beginning of the next century at the earliest, rather detailed engineering studies and cost estimates have been made. These studies have the purpose of providing adequate support for planning purposes and for establishing a relevant cost for disposal to be factored into the charge to the electricity consumer.

Although the contribution of the disposal cost to the total electricity generation cost is small, the absolute value of the cost for disposal is expected to be substantial. Some development costs will occur appreciably before disposal, but most will appear long after the corresponding electricity generation. In most OECD countries with a nuclear programme, funding schemes have therefore been established to make provisions for these costs. Fairly accurate estimates of the costs are thus required.

In this study, an international review of reported cost estimates for the disposal of spent fuel or reprocessing waste has been made. As the general situation and circumstances differ substantially between the countries, the bases for the cost calculations are very different and consequently the total estimated disposal costs vary widely.

The objective of the study has been to provide a better understanding of the origins of variations in the cost estimates and to discuss to what extent technical, political, social and economic factors could explain the variation.

Disposal concepts

For the management of spent fuel, two alternative approaches are considered in OECD countries: direct disposal of suitably packaged spent fuel as waste, and reprocessing of the spent fuel to recover the useful products it contains (uranium and plutonium), followed by disposal of the remaining waste products. Direct disposal of spent fuel is the main option in Canada, Finland, Spain, Sweden and the United States, while reprocessing is the main option in Belgium, France, Japan, the Netherlands, Switzerland and the United Kingdom. In Germany, both direct disposal and reprocessing are considered.

The wastes to be disposed of in the two approaches are physically quite different but put similar demands on the repository from the point of view of isolation and temperature restrictions. This means that the repository designs considered are quite similar and indeed some repositories will take both types of waste. For this reason disposal concepts for both spent fuel and reprocessing waste are considered in this report. The content of long-lived radioactivity in these wastes is such that deep disposal (at a depth of a few hundred to a thousand metres) is considered necessary. Short-lived wastes that may be disposed of near the surface are not considered in this report.

Several geological media are being considered for disposal, such as crystalline rock, salt, clay and schist. This range of possibilities naturally provides different conditions for the design, construction and operation of a repository. Consequently, a number of different repository designs have evolved in the different countries.

In general, however, there are many similarities in the repository designs. In all cases presented, the disposal system is based upon the multiple-barrier principle, *i.e.*, the use of multiple barriers, such as the waste form, a corrosion-resistant container, sealing systems and the geological medium. For direct disposal of spent fuel, a separate disposal container is always used, while for vitrified high-level waste (which is vitrified in a stainless steel canister) an extra container (overpack) is proposed only in some concepts. In other concepts for the reprocessing approach, the waste form and stainless steel canister are considered to provide an adequate first barrier. Different materials are used for the disposal container, such as iron, stainless steel, titanium, copper and ceramics. For the alpha-bearing waste from reprocessing, no extra disposal container is normally needed.

The reference design of the repository is, in most countries, based on a tunnel-and-drift design, where the waste packages are disposed of in boreholes drilled into the tunnel floors or in the middle of the tunnels and surrounded by a backfill material. In order to limit the temperature rise in the rock due to the decay heat released from the waste, the waste packages are distributed evenly throughout the rock with a certain separation. The detailed designs are dependent on the physical properties of the particular geological medium.

Cost results

Results of cost estimates have been reported internationally on many occasions. The results are presented in different ways, *e.g.*, total costs, discounted total costs, costs per kWh or funding demand. As the assumptions made are rarely described in any detail, such results do not lend themselves to intercomparisons. Depending on local conditions and on the national strategy, the costs could also cover some or all of the other steps in the spent fuel management process, such as interim storage, transportation, and reprocessing, in addition to final disposal. To be able to make a comparison between cost results, it is important to define clearly what is included in the costs.

In this report, twelve sets of undiscounted cost data for the packaging, and disposal of spent fuel or reprocessing wastes have been provided from eleven OECD countries. The data are given in the national currency at the base year of the cost calculation. For reasons of comparison, the costs have been converted in this report to July 1991 US dollars. The costs have been limited to the design, construction, operation, decommissioning and closing of the facilities. The costs for R&D, site screening and site evaluation, which could be a substantial part of the total costs, are not included, as their content varies widely and there is no basis for comparison between the countries. It should be recognised that these costs are more significant in discounted cash flow analyses because they appear early in the cash flow of the project.

Although packaging and disposal of spent fuel or reprocessing waste are new activities that have not yet been performed, the basic components involved in the process are often well understood because of similar applications in other areas of the nuclear fuel cycle or in other industries. The cost estimates are based on fairly detailed design and operation studies. Of course, a certain level of uncertainty exists in the methods proposed and thus in the estimated costs for repository construction and operation. Normally, therefore, rather high contingencies are included in the estimates. Furthermore, it should be noted that the present cost estimates are, by and large, preliminary. Therefore, great caution should be applied in the interpretation and comparison of the cost data.

As the disposal systems presented vary substantially in capacity, from waste corresponding to an electricity production of 430 TWh (1 800 tonnes of uranium) in the case of Finland to 23 000 TWh (96 000 tonnes of uranium equivalent) in the case of the US, the total costs will also be very different. There is also a difference between disposal of spent fuel and disposal of reprocessing waste, the latter generally being lower in cost. The total costs reported vary between US$ 0.8 and 10.0 billion for spent fuel disposal and between US$ 0.5 and 6.3 billion for disposal of reprocessing waste. It should be emphasized that the costs of reprocessing are not included in these cost estimates. The main cause of these variations is the size of the system, *i.e.*, the amount of waste to be taken care of.

If the costs are normalized with regard to total electricity production, the differences between the different estimates decrease. The normalized cost varies between $ 0.43 and $ 1.77 M/TWh for spent fuel disposal and between $ 0.25 and $ 1.65 M/TWh for disposal of reprocessing waste. A large part of this variation is due to the size effect. As a rather large fraction of the disposal costs are fixed, the specific costs will decrease with the size of the system. The usually applied fuel cycle normalization of "per tonne of uranium" is shown to introduce some major distortions if wastes from different reactor types are compared, and should be avoided.

Technical factors affecting costs

From the earlier description, it is quite clear that other factors also affect costs. As the data provided are not detailed enough to analyse them quantitatively, they are discussed qualitatively in the report.

The most important technical factors, after the size of the system and the choice between direct disposal and reprocessing, are the time schedule of the disposal project, the choice of geological medium and the barrier system chosen.

In most concepts there is a limitation in the maximum allowed thermal impact on the repository and surrounding structures. As the heat output from the fuel and high-level vitrified waste decreases with time as a result of radioactive decay, the waste can be disposed of in a more compact way following longer interim storage time. The time schedule can therefore have a significant impact on the disposal costs.

The different geological media considered have different geotechnical properties that will affect the construction and operation of a repository. In hard rock, for example, big tunnels can normally be kept open for a long time without installation of high-strength liners while in clay, the tunnels must be lined. Differences like these affect the design, construction and costs.

The most important difference between the various concepts concerning the barrier system is whether a separate disposal container is used or not, the material of the container and the type of packaging process. If a separate container is not used, the costs for packaging, which are substantial, do not arise.

Non-technical factors affecting costs

As the disposal of spent fuel or reprocessing waste is expected to be a highly controversial political issue in most countries, the social and political issues will inevitably affect the costs. They will affect, for example, the siting and licensing process (by political delays, demands for further investigations and procedural complications, etc.) as well as the overall waste management policy.

The effect of these social and political factors cannot easily be included as a straightforward cost factor in the cost calculations, but could be accounted for as an extra risk factor. Other social and political factors such as taxes, the cost of land, compensation and mitigation of impacts on the local population and the environment could, however, easily be included.

In the comparison of cost estimates, one complicating factor is the economic and financing considerations that are included in the costs as presented. This is particularly true for the funding estimates, where interest and discounting factors are included. As the time span over which the costs for disposal will occur is very long, these factors strongly distort the comparison. In this report, in order to avoid this complication, only undiscounted costs in price value of July 1991 US dollars are used. This means that the specific costs per TWh reported here are greater than the ones used to accumulate funds to cover the cost of disposal.

Conclusions

Cost estimates for the disposal of spent fuel or reprocessing waste have been made in many countries. In this report, twelve different estimates from eleven countries are reported and compared.

The estimates are based on design studies. As no disposal facility will be in operation until the beginning of the next century at the earliest, the costs must be regarded as preliminary and be treated cautiously, as a rather large uncertainty exists. In the cost estimates, a high contingency factor is normally applied. Although no packaging or disposal facilities yet exist, it should be recognised that many of the cost components are based on well-established experience in other nuclear and non-nuclear fields.

It has been determined that comparison of the cost estimates is very difficult and certainly should not be done without taking due account of the different bases on which the cost estimates have been prepared. The comparison is more meaningful after due normalization. In fact, considering the differences in system designs, there is surprisingly good agreement between the estimates when they are normalized with regard to total electricity production and the remaining differences can be explained at least qualitatively. This indicates that the disposal costs are reasonably well understood in the OECD countries.

The cost of disposal of spent fuel or waste from reprocessing is only a small fraction of the total electricity generation cost. The uncertainties in these costs indicated by the variation in the cost estimates presented here will therefore have only a marginal effect on the cost of electricity production from nuclear power.

Chapter 1

INTRODUCTION

Studies of the disposal of spent fuel or of reprocessing wastes* have been performed in all countries with a nuclear power programme. The development and demonstration of the technology for disposal and licensing is progressing well but operating disposal facilities will not be available in OECD countries until the beginning of the next century at the earliest. Extending the time between fuel discharge from a reactor and disposal provides the technical advantage of reducing the heat and radiation emissions from the waste due to radionuclide decay, offering the possibility of simplifying the design and reducing the size of a disposal facility.

Spent fuel or reprocessing wastes are highly radioactive, long-lived or toxic, and could represent a significant hazard to man and his environment, if not managed properly. It is essential that they be isolated from the biosphere for very long periods of time. The generally accepted method for isolation is disposal at depth in geological formations that provide a stable environment for a very long time.

The safety of disposal of such wastes has been described and discussed in numerous reports, including other NEA publications. Although no disposal facility has yet been constructed, no major technological problems are expected, as the technology to be used is based almost entirely on experience from other existing nuclear facilities, *e.g.*, reprocessing plants and disposal facilities for short-lived wastes, and from other non-nuclear areas.

The cost of disposal is expected to be substantial and will appear long after the corresponding electricity generation. In most OECD countries with nuclear power programmes, funding schemes have, therefore, been established to cover the future costs and a considerable amount of money has already been set aside.

As a basis for the funding schemes, estimates of the costs for disposal have been produced in OECD countries. As the conditions vary substantially between the countries, the results of these estimates have also shown a great variation. Therefore, it could be suggested that the costs of final disposal are not well founded. However, closer examination reveals good reasons for the differences, such as variations in the technical/engineering aspects and national disposal strategies, and non-technical issues such as schedule and financing assumptions.

Although the total costs are substantial, the contributions of the disposal costs to the total fuel cycle costs are small. A previous NEA study on nuclear fuel cycle costs [1] suggests that disposal costs in levelised cost calculations represent only a small percentage of the total fuel cycle costs. Therefore, even if there are significant fluctuations in the disposal cost estimates, they have only a small impact on the total cost of electricity generated by nuclear power stations.

Accurate estimates of the cost of disposal are, however, important for calculating the contribution to the funding scheme required to fund fully the cost of future disposal. This contribution is collected in the price charged for the sale of electricity. Too low a contribution will impose an economic burden on future generations, while too large a contribution will impose an undue burden on present electricity consumers. General equity considerations thus require that the estimated costs be as close as possible to the eventual costs.

The cost estimates are based on considerable technical knowledge from nuclear and non-nuclear activities and established geotechnical engineering experience. Therefore, although the cost estimates include a measure of uncertainty, major causes of the variations of the estimates relate to technical issues such as size of the nuclear power programme, waste form, disposal medium, selection of disposal system components, safety regulations, socio-political factors and economic assumptions. However, this has not been clearly and systematically established in previous studies. The NEA's economic studies [1, 2], where disposal costs entered into the total costs considered, did not focus on the causes of the variation.

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* In the remainder of this report, the term "reprocessing waste" is used as an abbreviation for "high-level vitrified waste and alpha-bearing waste from reprocessing activities".

Scope and goal

This study provides an international review of cost estimates for disposal of spent fuel or reprocessing waste in geological repositories. The principle objective of this study is to provide a better understanding of the origins of variations in the cost estimates, and to discuss to what extent various political, institutional, technical and economic factors could explain the variations. The main effort has been concentrated on identifying the factors that may affect the cost estimates for the packaging and disposal of waste. Other steps in the spent fuel management system will be discussed but not analysed in detail, as they are strongly dependent on the strategy adopted in each country.

In this study, the costs will be considered both for spent fuel disposal and for disposal of reprocessing wastes. It must, however, be emphasized that these costs should not be used for comparison between the direct disposal and the reprocessing routes, as not all the costs involved will be considered here. For example, in the case of the reprocessing route, neither the cost of reprocessing nor the value of the fissile material recovered is considered. The safety of the disposal will not be discussed in this report but has been covered in other publications [3, 4, 5, 6, 7].

Structure of this report

This report, intended for the general reader with an interest in this topic, discusses various points that should be considered when one examines disposal cost estimates. Chapters 2 and 3 briefly review the spent fuel management systems and disposal systems. Chapter 4 explains the cost components of the disposal. Chapter 5 provides the cost calculation procedures, and the results of cost calculations presented to the Expert Group are given in Chapter 6, which also includes a discussion on normalization methods of the estimates. These estimates form the main reference for the subsequent discussion. Chapter 7 describes the technical factors that affect cost calculations and Chapter 8 describes the non-technical factors. Chapter 9 provides the conclusions of the study. Specific details about cost calculations for current waste disposal strategies being studied in some OECD countries are given in Annex 1 at the end of the report. Annex 2 provides a list of abbreviations and glossary of terms used in the report.

Participants

This study has been undertaken under the auspices of the NEA's Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). The preparation of the study has been overseen by an Expert Group whose membership is listed in Annex 3. Twelve OECD countries and two international organisations have participated in the study.

Decommissioning costs

A similar study has been performed for decommissioning cost estimates. The objective of that study was to make clear the causes of the variation in the cost estimates for decommissioning nuclear power plants. The study report was issued September 1991 [8].

Chapter 2

SPENT FUEL MANAGEMENT SYSTEM

2.1. General

The management of spent fuel starts with the discharge of the fuel from the reactor core to fuel storage in the nuclear power plant and ends with the disposal of the fuel or its waste residues. Two general approaches to spent fuel management are being considered:

- **the reprocessing approach,** in which the spent fuel from the reactor is reprocessed, to separate plutonium and uranium, which can be reused as nuclear fuel, from other radioactive elements produced in the fission process in the reactor core;
- **the direct disposal approach,** in which the spent fuel is not reprocessed but is disposed of as a waste product following appropriate treatment.

The selection of an approach to spent fuel management by a country or utility is based on the consideration of a number of factors. These may include national nuclear strategy, regulations, costs and social effects. As each of these factors may have different meanings and implications in each country, the spent fuel management strategies may vary both in technical detail and in schedule.

Irrespective of the approach chosen, a number of steps and actions must be taken in order to manage the spent fuel safely. In Figure 2.1, the different stages of spent fuel management are illustrated schematically. The figure also provides an indication of the quantities of the material involved in the different stages for each one-year operation of a 1 000 MWe pressurized water reactor (PWR). As the mass balance is affected by various technical factors, the quantities indicated in Figure 2.1 are for illustration only.

This economic study focuses on the costs for packaging and disposal of spent fuel in the direct disposal approach, and of reprocessing wastes in the reprocessing approach. The costs for reprocessing, interim storage and transport are not considered in this study. If a cost comparison between the two spent fuel management approaches is the objective, the costs for all stages of spent fuel management, as well as the value of the recycled material, must be included. Such a comparison has been done by others [1, 9, 10].

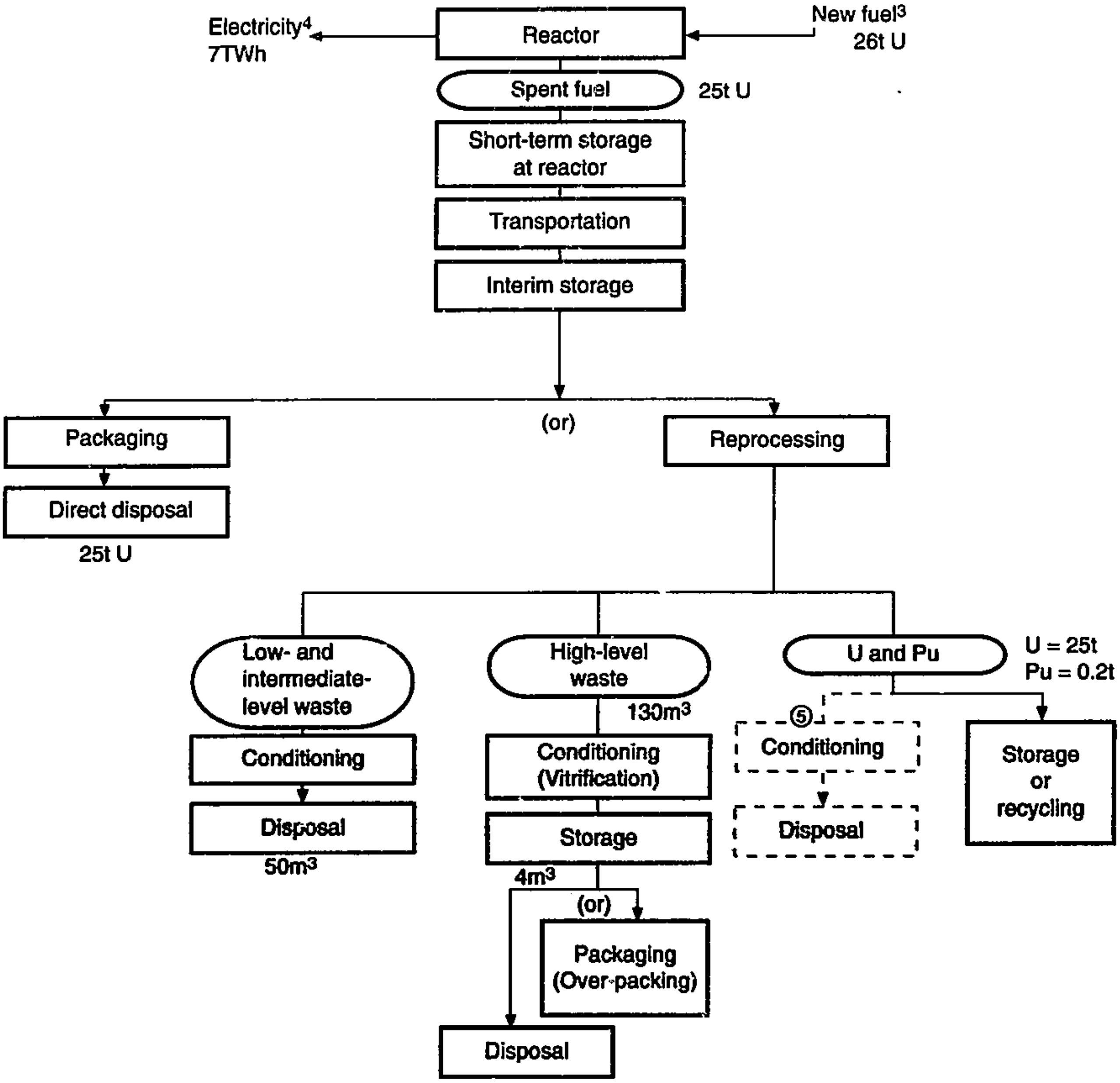
In the remainder of this chapter, an overview is given of the main components of the spent fuel management system, and the characteristics of the spent fuel and the wastes to be considered are described. A more detailed explanation of the final disposal stage, including packaging as needed, is given in Chapter 3.

2.2. Spent nuclear fuel

The fuel for a light water reactor (LWR) consists of cylindrical pellets of sintered uranium dioxide enclosed in rods of zircaloy. The rods are bound together in fuel assemblies that are handled as units. A fuel assembly for a 1 000 MWe PWR typically contains about 250 fuel rods and has a length of about 4 m. Figure 2.2 shows a typical PWR fuel assembly. The content of uranium is about 500 kg per assembly. The uranium is initially enriched to 2-4 per cent uranium-235.

Other reactor types have other fuel designs. Some data of typical fuel assemblies are given in Table 2.1. A boiling water reactor (BWR) fuel assembly is very similar to that of a PWR but has fewer rods and only about 200 kg of uranium. A heavy-water reactor (HWR) fuel bundle is about 50 cm long and 10 cm in diameter, consisting of 19 to 37 individual cylindrical pins of natural uranium dioxide, and containing about 19 kg of uranium per assembly. In advanced gas-cooled reactors (AGR), uranium dioxide fuel encased in stainless steel rods is used. The assemblies are about 1 m long and contain 36 rods in a graphite cylindrical sleeve, totalling about 42 kg of uranium enriched to 2.5 per cent. In Magnox gas-cooled reactors, uranium metal encased in a

Figure 2.1[1] **Stages of spent fuel management and quantities[2] of the materials involved in the different stages**



1) This figure is prepared on the basis of an NEA report; *The Economics of the Nuclear Fuel Cycle*, Paris, 1985.
2) Quantities for each one-year operation of a 1000 MWe PWR.
3) 3.1% enrichment, for 33000 MWd / t U.
4) With a load factor of 80%.
5) Recovered U and Pu may be disposed of after recycling a number of times.

Figure 2.2 **A new fuel assembly of a PWR**

Photo: Électricité de France

magnesium alloy is used as fuel. The fuel elements are 1 m long and contain about 12 kg of natural uranium. Other less common types of spent fuel come from research reactors, fast breeder reactors, etc.

When the fuel assembly is discharged from the reactor, it is still handled as a unit and its appearance is generally similar to fresh fuel. The fuel, however, is highly radioactive and emits radiation and heat, as it contains uranium, plutonium, fission products and other actinides, such as neptunium, americium and curium. A typical

Table 2.1. **Characteristics of typical fuel assembly**[a]

	PWR[b]	BWR[c]	CANDU	Magnox	AGR
Approximate fuel assembly dimensions (cm)					
– Length	435	447	50	100	100
– Cross section					
Side (square)	23	14			
Diameter (cylinder)			10	10	24
Fuel weight (kgU/assembly)	531	184	19	12	42
Average fuel enrichment (w/o)	2.4/3.5	3.1	0.7	0.7	2.5
Average burnup (MWd/kgU)	42	36	8	5.5	18

a) Prepared on the basis of "Guidebook on Spent Fuel Storage, Second edition", Technical Report Series No. 240, IAEA, Vienna, 1991.
b) Rod array: 18 x 18. Number of rods: 300.
c) Rod array: 9 x 9. Number of rods: 76.

LWR spent fuel (3.1 per cent enrichment; 33 000 MWd/tU* burnup) consists of about 96 per cent uranium, 1 per cent plutonium and 3 per cent fission products and other actinides [1]. These materials are contained in the uranium dioxide fuel matrix. For a 1 000 MWe PWR, typically 25 tU** of spent fuel is generated annually.

The radioactivity of the spent fuel decreases with time. At first, the decrease is very rapid as the short-lived radionuclides decay. As time passes, the radioactivity decreases more slowly, as it is controlled by the decay of the more long-lived radionuclides. The decrease in radioactivity results in a corresponding decrease in heat generation. In Figure 2.3, the evolution of heat generation with time after discharge from the reactor is shown for typical PWR spent fuel. One year after discharge, the radioactivity content is about 73 000 TBq/tU, and the heat generation is about 8.1 kW/tU. In Figure 2.3 also, the evolution of heat generation with time for typical high-level vitrified waste is shown.

Other fuel types will have other burnups and, consequently, other absolute levels of radioactivity and heat generation. Typical examples of heat generation at one year after discharge are: 3.2 kW/tU for CANDU fuel (approx. 8 000 MWd/tU), 1.0 kW/tU for Magnox fuel (approx. 5 500 MWd/tU) and 4.0 kW/tU for AGR fuel (approx. 18 000 MWd/tU). The time behaviour of these quantities will, however, be pro rata to the PWR fuel.

2.3. Outline of spent fuel management

2.3.1. General

As was shown in Figure 2.1, a spent fuel management system typically includes some or all of the following steps:

- storage at reactor;
- transportation;
- interim storage;
- reprocessing;
- packaging/conditioning;
- final disposal.

In the following paragraphs, each of these steps is briefly described.

2.3.2. Storage in spent fuel cooling pond at the reactor site

After being discharged from the reactor core, the spent fuel is placed in a pond or in dry storage where it is cooled and its radiation field is contained by shielding. While in storage at the plant, the short-lived fission products decay rapidly and the heat output decreases correspondingly. With LWR fuel, for example, the heat from a fuel assembly (0.46 tU, 33 000 MWd/tU) is 17 kW after one month, 4 kW after one year and 0.8 kW after five years from the time of discharge from the reactor.

The length of the cooling period at the reactor may vary from less than a year to a few decades, depending on the national nuclear policy, the availability of a reactor or an interim storage capacity, the reprocessing capacity and/or the disposal facility. If a long on-site storage period is planned, the fuel will in some cases be transferred from a reactor storage pond to a dry storage facility or an auxiliary wet storage facility. Dry and wet storage facilities are already in operation. Details of at-reactor storage are reported in, for example, IAEA reports [11, 12].

2.3.3. Transportation

After the initial period of spent fuel storage at the reactor site, transportation is an essential part of spent fuel management, irrespective of the approach chosen. The transportation of spent fuel is a well-established practice that has been performed on a routine basis for more than 20 years. Transport is by truck, rail, or ship. The transportation standards are covered by the IAEA Regulations for the Safe Transport of Radioactive Materials [13] and controlled by specific regulations issued by individual governments. These regulations require,

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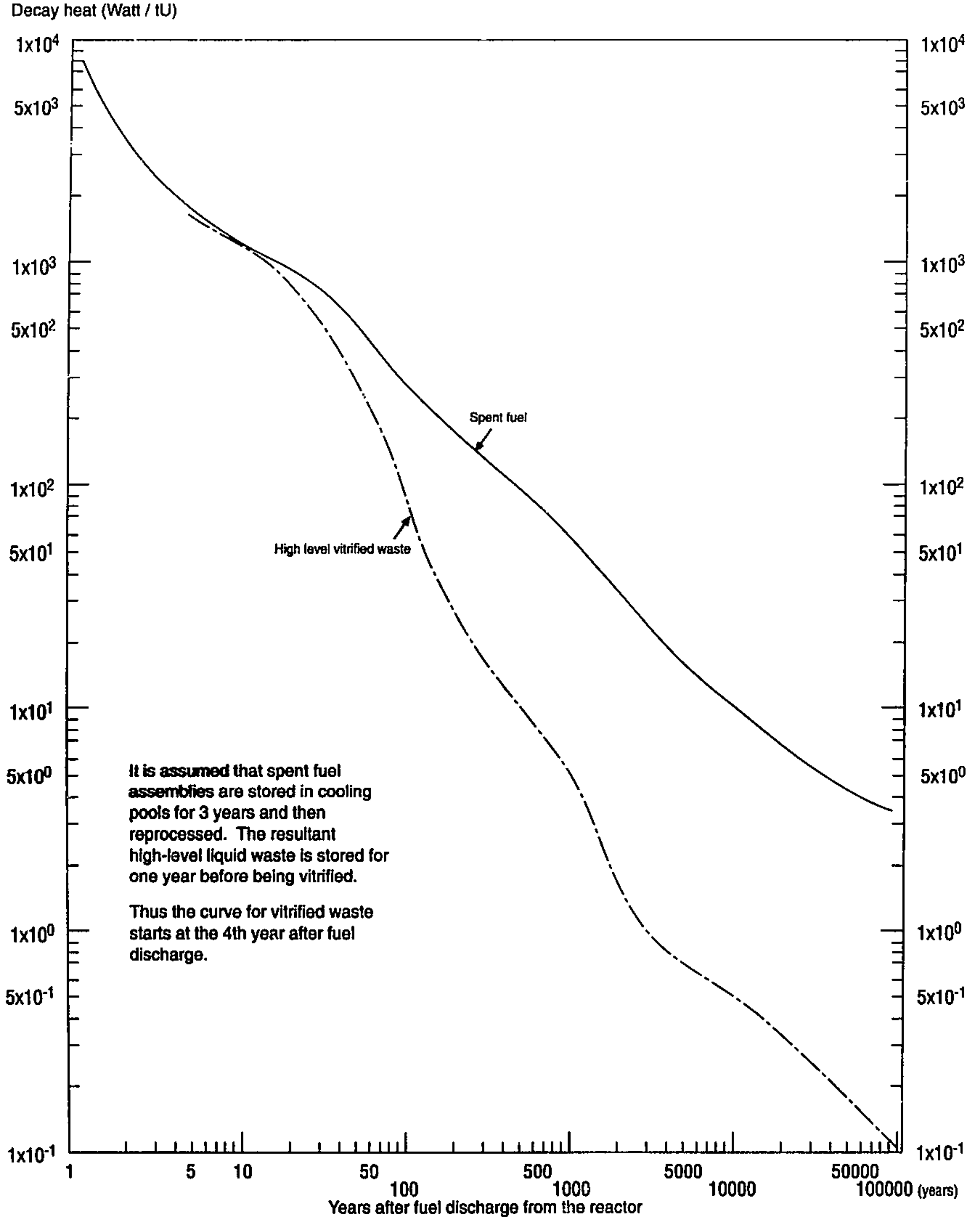
* In this report, burnup is consistently given in MWd/tU, although MWd/tHM (tonne of heavy metal) is more precise.

** In this report, the amount of nuclear fuel is consistently given in tU (tonne of uranium), although tHM (tonne of heavy metal) is more precise.

Figure 2.3 **Evolution of decay heat from 1 tU of spent PWR fuel (irradiated to 33 000 MWd/tU) and corresponding high-level vitrified waste**

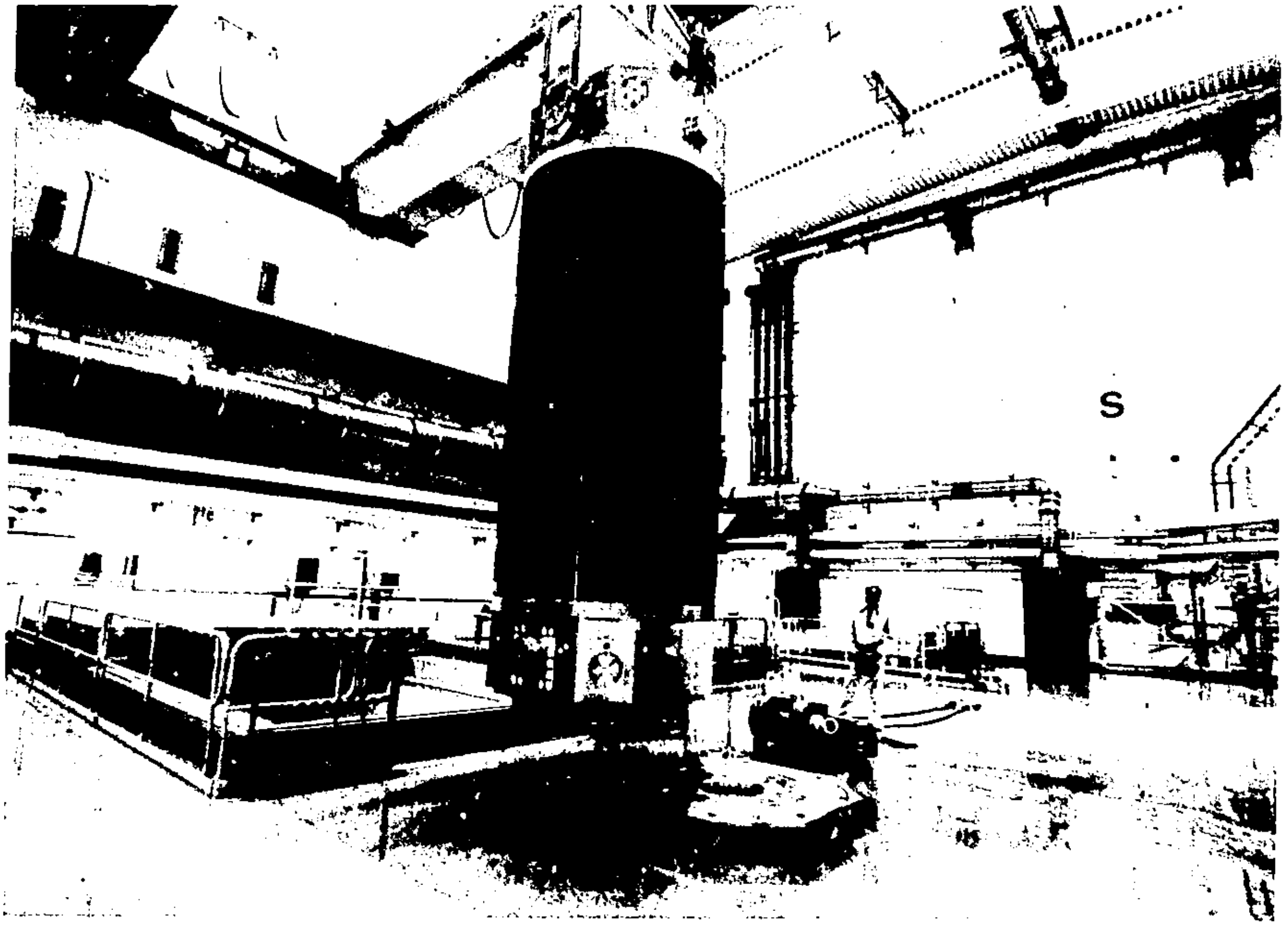


It is assumed that spent fuel assemblies are stored in cooling pools for 3 years and then reprocessed. The resultant high-level liquid waste is stored for one year before being vitrified.

Thus the curve for vitrified waste starts at the 4th year after fuel discharge.

Figure 2.4 **Transport cask for spent fuel (Sweden)**

Photo credit: Mr. B. Emmark



among other things, that a prototype of each transport cask undergo specific tests that simulate severe accident conditions as part of the licensing process.

A transport cask for spent fuel is a massive box or cylinder weighing 50-120 tonnes that can hold 1-8 tonnes of fuel. The thick cask walls made of steel, together with shielding made of steel, depleted uranium and/or a material containing hydrogen, such as polyethylene or paraffin wax, provide ample radiation shielding for gamma and neutron radiation. The casks are also designed to dissipate the heat generated in the fuel. The need for radiation shielding and heat dissipation decreases with time and the design of the cask and safety case will relate specifically to a heat load that is a function of fuel mass and cooling time. Figure 2.4 shows a typical transport cask.

The transport casks for high-level vitrified waste and some of the alpha-bearing wastes from reprocessing will be of similar design to those for spent fuel, but specially designed for the radiation, heating and geometric characteristics of the waste package to be transported.

2.3.4. Interim storage of spent fuel

In some strategies of spent fuel management, spent fuel will be transferred from the cooling ponds at the reactor site to interim storage facilities away from the reactor site and stored there for some time before reprocessing (in the reprocessing approach) or conditioning prior to disposal (in the direct disposal approach). The necessity for the interim storage and the length of the storage period is determined by the capacity of the storage facilities at the reactor and the availability of the reprocessing capacity or of the disposal facility. In some national strategies, extended storage is often used to allow radioactive decay to reduce the heat generation of the spent fuel before disposal, thereby changing the specifications for the disposal system.

In cases where the cooling pond at the reactor site has sufficient capacity or where the pond or dry storage capacity could be reasonably expanded, interim storage could take place at the reactor. In this case, the spent fuel could be kept in interim storage at the reactor site for several decades.

The location of an interim storage facility will be dependent on national circumstances. It is often co-located with a reactor and it could serve one reactor or all the reactors in the country. Alternatively, it could be located at the reprocessing or disposal site or at a separate location. In some countries, a considerable amount of fuel will accumulate and will be stored for a relatively long period. This may favour the development of large-scale central facilities dedicated to the storage of spent fuel and seeking to take advantages of economies of scale, although requiring additional waste transportation.

Various approaches have been developed for interim storage [14, 15]. In some approaches, the fuel assemblies are stored in ponds where they are cooled by water. In other approaches, the fuel assemblies can be safely held in dry storage (*i.e.*, dry pits, dry casks, etc.) where cooling is accomplished using either air or inert gases with natural or forced circulation. The fuel assemblies are normally stored intact. In some cases, the assemblies are disassembled (rod consolidation) to achieve a closer packing and hence a volume reduction. In many cases, the waste is sealed in specially designed storage containers.

2.3.5. Reprocessing

The technology of spent fuel reprocessing is well-established and used on a commercial scale in France and the UK. The purpose of reprocessing is to separate uranium and plutonium from other actinides and fission products contained in the spent fuel. The fuel is dissolved in nitric acid, and uranium and plutonium are separated in a chemical process (*e.g.*, the PUREX process). The uranium and plutonium recovered are recycled for possible subsequent use as nuclear fuel. The rest (other actinides, fission products and impurities) become a highly radioactive solution (high-level liquid waste) and are stored for further conditioning. Figure 2.5 shows an aerial view of the La Hague reprocessing plant in France.

During operations at the reprocessing plant, several separate categories of radioactive waste are produced.

The **high-level liquid waste** contains more than 99 per cent of the non-gaseous fission products, together with traces of plutonium and other actinides. The waste may be concentrated by evaporation and stored in stainless steel tanks, which are water-cooled, double-walled, and situated in shielded facilities.

For interim storage and final disposal, the waste is converted to a stable solid form. The most common solidification method is vitrification with borosilicate glass in a stainless steel canister. Other processes involving glass or ceramics are considered. Vitrification processes and the characteristics of the vitrified materials have been studied intensively and the methods have been adopted for industrial-scale operation in many countries (Belgium, France, Germany, Japan, the UK). Vitrification provides a low-volume solid waste form. Vitrified waste is chemically durable and has suitable physical and thermal properties for long-term storage and disposal. An artist's impression of vitrified high-level waste is shown in Figure 2.6.

The amount of vitrified waste from a 1 000 MWe PWR will typically be about 4 m^3/year. The dimensions, chemical characteristics and radioactivity of the waste are affected by the methods and specifications of the vitrification process. Table 2.2 provides some information on typical vitrified waste.

The rate of radioactive decay and the decrease in heat generation of the vitrified waste is at first comparable to that of the spent fuel, as the radioactivity is dominated in both cases by the fission products. After some time, the plutonium nuclides and their daughter products come to dominate the decay of the spent fuel, and the decay of vitrified waste then becomes more rapid, as shown in Figure 2.3.

Intermediate-level liquid wastes are usually contaminated with alpha-emitting radionuclides. The wastes can be processed to concentrate their radioactive content, which can then be added to the high-level waste stream, or alternatively immobilised into a solid matrix such as concrete, bitumen, or resin. **Low-level liquid wastes** contain very little radioactivity and are disposed of after appropriate treatment or discharged under carefully controlled conditions.

Solid wastes include the cladding removed from the spent fuel, filters, resins and other materials used during the reprocessing operation, and contaminated plant and equipment. The wastes are radioactive to various

Figure 2.6 **Artist's impression of vitrified HLW in a stainless steel canister**
Nuclear Electric diagram from BNFL photo

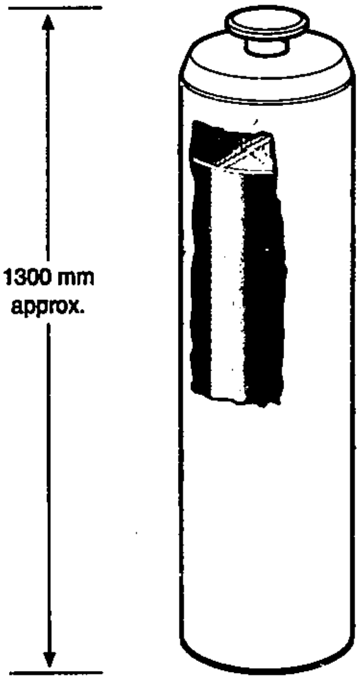


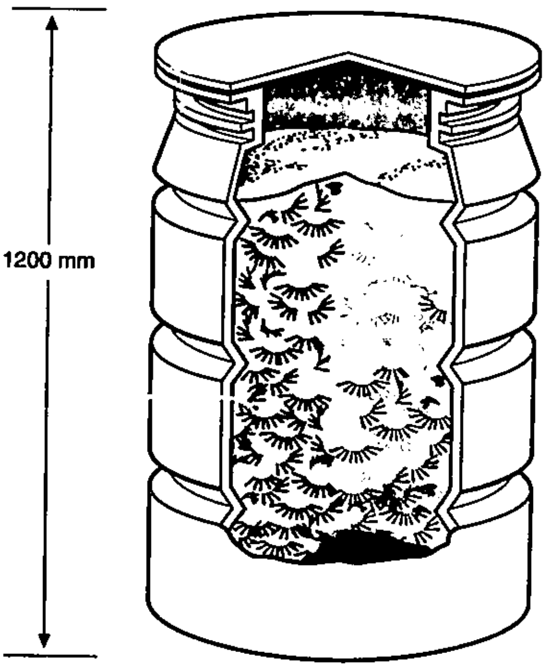
Table 2.2. **Characteristics of typical high-level vitrified waste**[a]

Approximate dimensions (cm) (cylinder)	
– Length	134
– Diameter	43
Capacity (l)	
– Nominal	170
– Glass	150
Weight (kg)	
– Total (canister and waste)	490
– Canister	80
Solid matrix	Borosilicate glass
Material of canister	Stainless steel
Radioactivity at the time of vitrification[b]	alpha: 140 TBq/canister beta-gamma: 28 000 TBq/canister
Heat generation rate at the time of vitrification	3 000 W/canister

a) COGEMA specification.

b) It is assumed that spent fuel is stored in cooling pool for 3 years before reprocessing and that the resultant high-level liquid waste is vitrified after 1 year of storage.

Figure 2.7 **Artist's impression of reprocessing ILW (finned Magnox fuel cladding) solidified with cement in a stainless steel package.** Nuclear Electric diagram from BNFL photos



degrees and most of them are contaminated with alpha emitters. After possible volume reduction by incineration, compaction or shredding, the wastes are immobilised into a solid matrix such as concrete or metal for disposal. Figure 2.7 shows an artist's impression of such waste.

Gaseous wastes are produced during the chopping up and dissolution of the spent fuel. After removing radioactive particulate materials by filtering and then removing some gaseous wastes by chemical processes, the remaining gases are discharged under carefully controlled conditions to the atmosphere.

Some of the non-high-level waste streams described in the preceding paragraphs contain long-lived radionuclides in quantities that make geological disposal appropriate. The dividing line between wastes with contamination levels suitable for other disposal routes, and those for which geological disposal may be appropriate, depends on their actinide content, their conditioning, the characteristics of the disposal system and national regulations. Because of their relatively low level of radioactivity and low rate of heat generation, these wastes may be handled in a simpler way than high-level wastes and spent fuel. Typically, 50 m^3/year of conditioned alpha-bearing waste is generated from the reprocessing of fuel from a 1 000 MWe PWR.

2.3.6. Interim storage of waste from reprocessing

In most countries that have taken the reprocessing approach, interim storage is also considered for reprocessing wastes during the period between conditioning and final disposal, (*e.g.*, several decades). This storage provides flexibility for the disposal schedule as well as the advantage of a lower heat generation rate in the vitrified waste at the time of final disposal, due to radioactive decay during the storage period. The rate of heat generation decreases by a factor of 50 or more between the first and the hundredth year after reprocessing. The storage facility is, in some countries, assumed to be located at the reprocessing plant site or final disposal site.

2.3.7. Packaging and final disposal

Although no countries have experience with commercial-scale disposal of spent fuel or reprocessing wastes, intensive research and development programmes for disposal have been pursued in almost every country with a nuclear programme.

The only disposal method considered at present is geological disposal, where appropriately packaged wastes will be disposed of in repositories which will be constructed between several hundred and one thousand metres underground. The repository for disposal of radioactive waste must provide a high isolation capability and be adequately stable. The repository design has to be optimised for each site, bearing in mind the type of waste, the type of host rock, site-specific conditions and so on. A more detailed description is given of the disposal methods considered at present in Chapter 3.

The safety of final geological disposal is generally accomplished by the use of multiple barriers, *e.g.*, the waste form, a corrosion-resistant container, a sealing system and the geological media in which the disposal facility is built. In the design of a disposal system, the balance amongst different barriers has to be considered and safety can only be judged from analyses of the entire system. This means that in some cases a thick-walled, long-lived container is used, thereby relieving some of the demands on other barriers, while in other cases no corrosion-resistant container is taken into account in the safety analyses. The latter could, for example, be the case for vitrified waste and some of the alpha-bearing waste, where the container used in waste conditioning is also the disposal container.

For spent fuel disposal, a corrosion-resistant container (more exactly, canister) is normally considered in order to ensure safe handling during the emplacement of the waste and a longer-term containment of radionuclides in the repository in order to limit and delay for a significant period any release of radionuclides from the waste.

The canister may also be constructed so as to provide adequate radiation shielding during handling for manually controlled transport and emplacement. Alternatively, a thinner canister may be used to reduce the amount of non-radioactive material disposed of with the waste but it will require remote handling or an additional overpack or cask for handling purposes.

For the disposal of alpha-bearing waste, there are generally no requirements for additional packaging. The primary packaging is often considered to be adequate for disposal. During handling, however, an extra overpack or cask may, in many cases, be required for shielding purposes.

After waste packages have been emplaced in the repository, the residual space in emplacement drill holes and in excavated tunnels will be filled by backfilling materials, such as spoil from excavations, bentonite, and cement. In many disposal strategies, excavation and preparation of additional disposal tunnels, backfilling and sealing are planned to be carried out concurrently with waste emplacement. When the emplacement of waste and a period of monitoring, if required, have been completed, the access tunnels and shafts will be backfilled and the surface facilities will be decommissioned. The site may be released for unrestricted use. In some countries, however, it is foreseen that long-term institutional control of the area will be necessary.

Chapter 3

GEOLOGICAL DISPOSAL CONCEPTS

3.1. Introduction

Within geological disposal, there are many alternatives. The choice of multiple barriers is important, as described in Chapter 2. Furthermore, the details, and subsequently the costs, are affected by the geological media, national regulations, site conditions, location of packaging facilities, and other factors. This chapter provides a detailed description of the packaging and disposal methods considered in OECD countries.

3.2. Packaging facility concepts

3.2.1. General overview

The packaging of spent fuel and reprocessing wastes involves sealing them in engineered containers* that are designed to have a significant period of structural integrity in the conditions expected at the disposal site. The containers for packaging either spent fuel or reprocessing waste will be designed to satisfy the specific requirements of the national disposal strategy, the regulations in force in that nation and the disposal site conditions. The container structural integrity contributes to a disposal strategy in two ways. First, the container will be an absolute barrier to the release of radionuclides from the waste to the natural environment for the time it takes for the container to corrode through. Further, the container will be structurally sound for an additional period of time during which it can facilitate waste retrieval if this is required.

Of the container concepts considered, two different categories can be distinguished. One category refers to containers with an expected service life of a few hundred years to a few thousand years. Materials discussed for these containers are carbon steel, stainless steel and titanium. The other category refers to containers with expected service life of hundreds of thousands of years. These containers are generally made of copper or ceramics.

In addition, a distinction can be made between a solid container, where all voids in the loaded container are filled with some supporting material, and a self-supporting container, whose walls are strong enough to take up the rock and groundwater pressure without any detrimental deformation.

A third categorisation distinguishes between containers that will provide adequate shielding for handling, and those for which a transfer cask or an overpack will be needed during handling and disposal.

The packaging operation will begin with the receipt of intact spent fuel assemblies from a storage facility or reprocessing waste from a reprocessing facility and end with the shipment of disposal containers to the disposal facility.

3.2.2. Spent fuel packaging

Spent fuel will be shipped from the nuclear generating stations or interim storage facilities to the packaging plant in licensed shipping casks whose capacity will depend on the method of transport (road, rail or ship) and the age of the fuel. The geometry of the spent fuel assemblies has been described in Chapter 2.

At the packaging facility, the shipping casks of spent fuel will be received and unloaded. After unloading, the casks will be resealed, decontaminated and returned to the shipper. The fuel may be packaged as received, or

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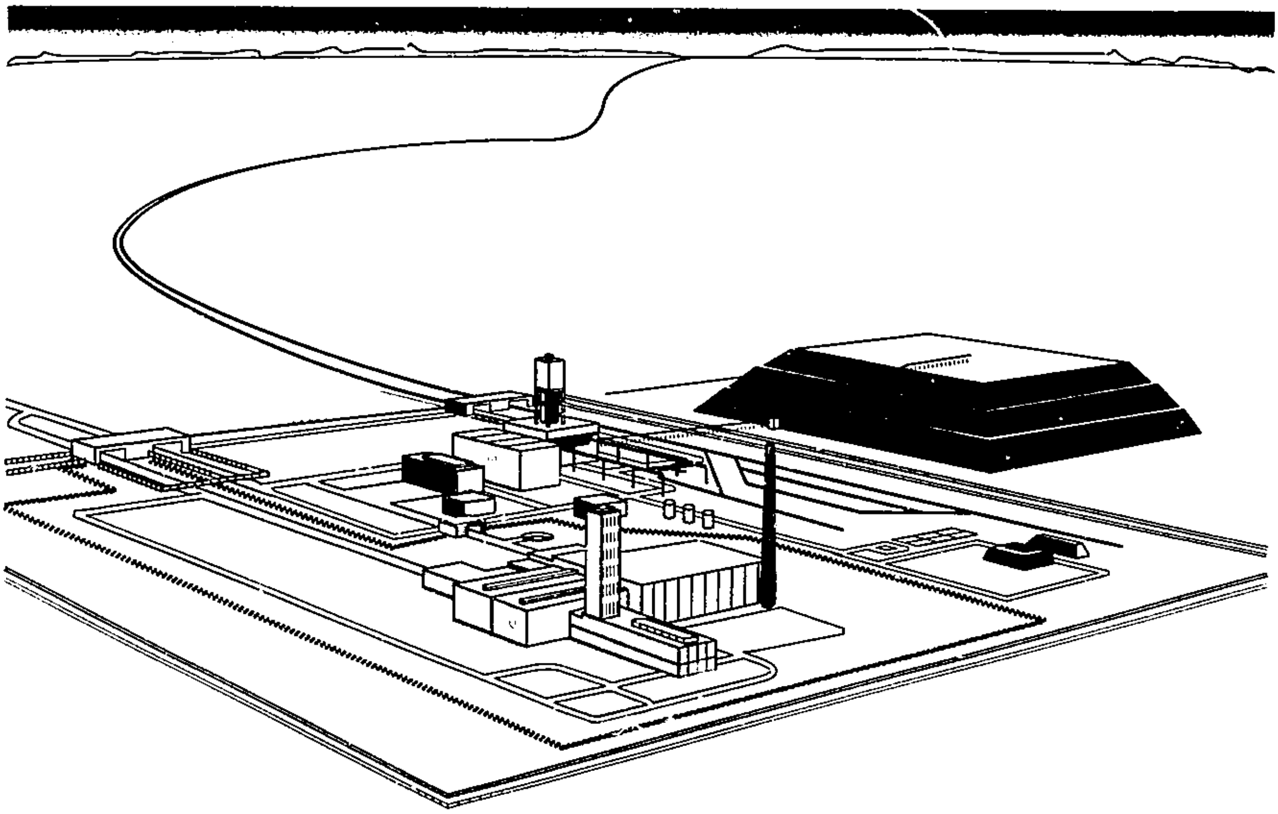
* Hereafter, the word "container" is a generic word for disposal purposes, and includes "canister" and "overpack". A canister is a closed or sealed container for spent fuel or reprocessing waste. An overpack is a secondary external containment and/or shielding for radioactive waste packaged in a canister (see Glossary).

may be disassembled and packaged in a more compact form. In either case, shielded hot cells will be required to allow these operations to be conducted safely and to control the spread of radioactive contamination, particularly if the fuel assemblies are disassembled prior to packaging. Temporary storage facilities are likely to be included to smooth the material flows through the receiving and packaging operations. These could accommodate both the fuel assemblies and the packaged waste.

The packaging process will involve the fabrication, loading, sealing and inspection of disposal containers. The container geometry and design will be a function of the fuel and repository design. The facility will provide the means for identifying the authenticity of the spent fuel for safeguards* purposes, transferring the fuel assemblies or their components to the containers, sealing, inspecting and decontaminating the containers, and storing them for transfer to the repository. If the process chosen includes the disassembly or chopping of fuel assemblies to improve the flexibility of packaging, there will also be fuel assembly hardware and fuel scrap from this processing that must be handled as waste. Most of these operations will have to be performed remotely in hot cells.

A packaging facility will be a rather large industrial complex. An example of the layout of a packaging facility is shown in Figure 3.1, and in Figure 3.2 a typical flow diagram for a packaging (more specifically "encapsulation") process is shown.

Figure 3.1 **Artist's view of packaging facility and surface facilities**
(Spain, for a salt formation)



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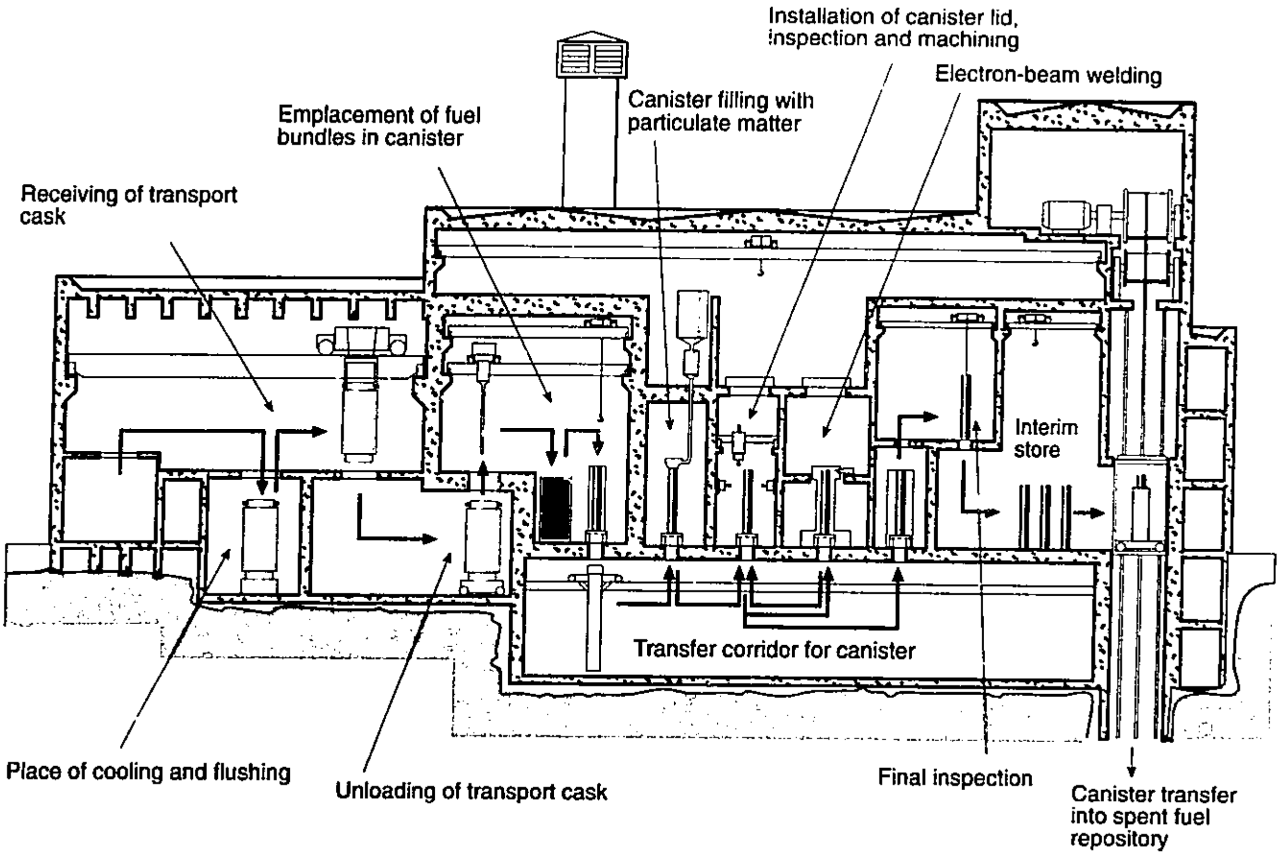
* Safeguards are measures to prevent or detect the diversion of nuclear material and to protect against the sabotage of facilities. The safeguards employed by a nation (domestic safeguards), which sometimes cover measures for physical protection, may be different from the IAEA safeguards (international safeguards). The term "safeguards" used here includes both. Please see Glossary (Annex 2).

Figure 3.2 **Typical flow diagram of packaging**
(Finnish encapsulation facility)



Additional supporting site service installations will supply the process utilities, waste treatment, trades, stores and warehousing, administration and management needed to operate the packaging plant.

Packaging of spent fuel has been studied in many countries, *e.g.*, Canada, Finland, Germany, Sweden and United States. The choice of container material and design is different in the different countries, reflecting differences in the natural conditions, in the fuel and in the size of the operation. These are briefly discussed in the following sub-sections. More details and references are given in the Countries Annex (Annex 1).

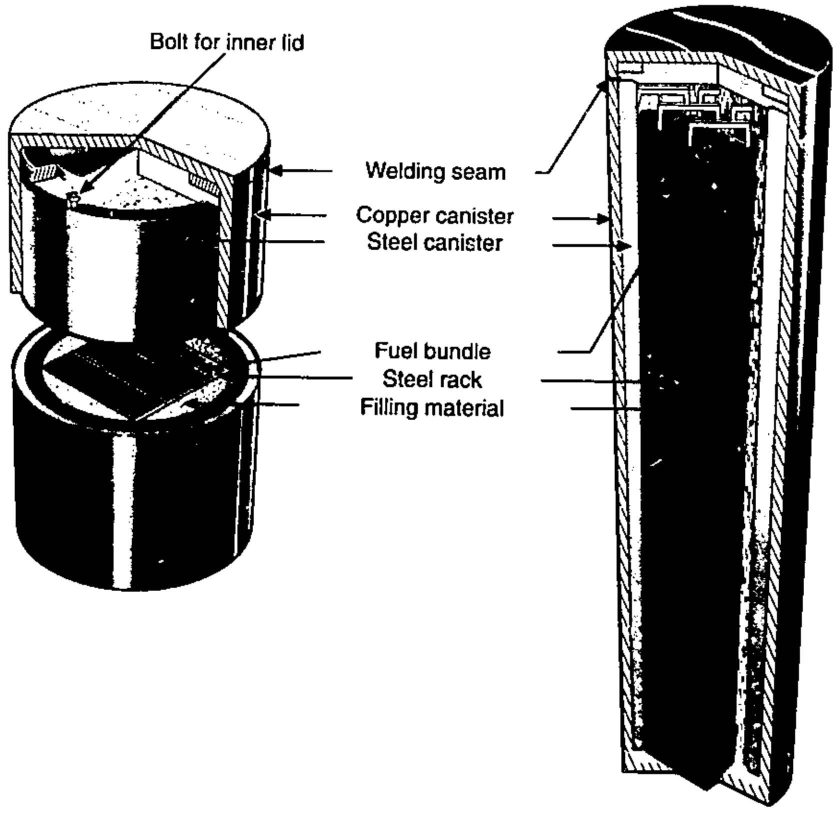
3.2.2.1. Canada

In the Canadian disposal concept, a container fabricated of 6.35-mm-thick grade 2 titanium has been selected as the reference container used in a conceptual engineering study [16]. In the container, 72 irradiated HWR CANDU fuel bundles, corresponding to about 1.4 tU, are packed in a basket consisting of storage pipes. All void space in the container will be filled with a particulate, such as glass beads, that will be vibrationally compacted to a sufficient density to support the container shell against the expected external hydraulic and mechanical loads. The top head will be installed on the container and sealed by diffusion bonding.

The container has been designed to:

- be structurally durable for a period of 500 years after emplacement;
- be amenable to manufacture and inspection, and sparing in its use of non-renewable critical resources required for its manufacture; and
- withstand external pressures of 10 MPa from hydrostatic head and 1 to 3 MPa from the swelling of clay-based sealing materials at a temperature of 100°C.

Figure 3.3 **Canister for spent nuclear fuel (Finnish concept)**



3.2.2.2. Finland

In the Finnish disposal concept, a composite container (Figure 3.3) has been proposed consisting of a 50-mm-thick steel container placed inside a 50-mm copper container [17]. Each container will take 9 BWR fuel assemblies equivalent to 1.6 tU. The void space is planned to be filled with a particulate, *e.g.*, lead shot. The lid of the inner steel container will be bolted, while the lid of the outer copper container will be welded.

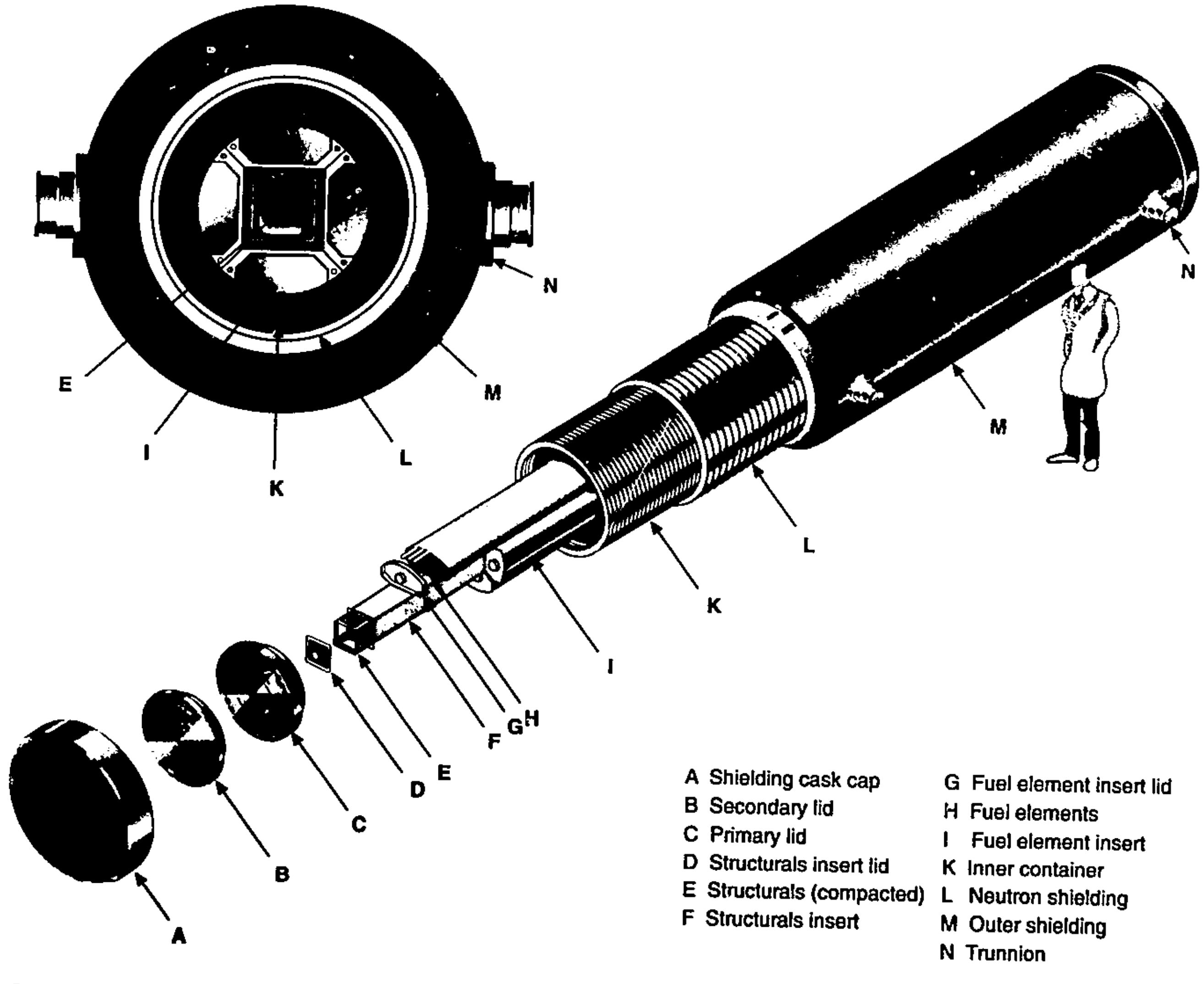
The inner steel container will make the container self-supporting, and the outer copper will give the container a very long service life (corrosion resistance).

3.2.2.3. Germany

In the German disposal concept for spent fuel, the so-called POLLUX cask (Figure 3.4) has been proposed [18]. This consists of a thick-walled, 150-mm, container of reactor steel. Each container can take fuel rods and structural parts from 8 PWR or 24 BWR dismantled fuel assemblies corresponding to 4 tU. The fuel rods are loaded into the inner container and a lid is bolted onto it. Then a second lid is placed on the container and seal-welded. In addition, this container is placed in an outer shielding overpack, thus completing the POLLUX cask.

The container is designed to withstand mechanical stresses due to rock pressure. It also provides adequate shielding during handling and disposal.

Figure 3.4 **Pollux cask**



Credit: **Gesellschaft für Nuklear Service (GNS)**

3.2.2.4. Spain

The Spanish disposal concepts, developed for two different geological media, granite and salt, consider drift disposal of intact spent fuel packaged in steel containers in a mined repository. The container capacity is 3 PWR or 9 BWR fuel assemblies for the granite option and 4 PWR or 12 BWR fuel assemblies for the salt option.

3.2.2.5. Sweden

In the Swedish disposal concept, a thick-walled, 100-mm copper container has been proposed [19]. The container can accommodate up to nine BWR fuel assemblies or 1.6 tU. After the fuel assemblies are placed in the container, the void space in the container is filled with molten lead and a copper lid is welded on. As an alternative, hot isostatic pressing of the container backfilled with copper powder has been considered.

The container is designed for a very long service life (corrosion resistance) and to withstand the external pressure from the hydraulic head, the rock and the swelling pressure of the clay used as backfill around the container.

3.2.2.6. United States

In the US disposal concept, a 9.5-mm-thick stainless steel container has been proposed [20]. Each container will take 4 PWR assemblies, or 10 BWR fuel assemblies, corresponding to about 1.8 tU or a combination of 3 PWR and 4 BWR assemblies, corresponding to 2.1 tU. No special filling of the void in the container is planned, as the borehole in which the container would be emplaced has a steel lining and no external force is anticipated during the required performance duration. The container will be sealed by welding a lid onto it.

3.2.3. Vitrified high-level waste packaging

The high-level waste will be immobilised and packaged at the reprocessing plant for safe shipment to the overpacking facility or to the repository, depending on the strategy adopted. The degree of additional packaging required beyond that done at the reprocessing plant will depend on the suitability of the initial immobilisation and packaging for disposal and on the other barriers in the repository. In some cases the packages may be transferred directly to the repository, while in others a corrosion-resistant container may be required.

In the Belgian, French, German and Dutch studies, no extra container is considered, while overpacking has been included in the UK, Japanese and Swiss studies.

The facilities and operations for the overpacking will be very similar to those for packaging of spent fuel, although somewhat simplified. In the UK study, a 65-mm mild steel container is considered for corrosion retardation [21], while in the Swiss study a very thick self-supporting cast steel container (250-mm-thick) is described [22]. In the Japanese study, a similar container is considered [23].

3.2.4. Packaging of alpha-bearing waste from reprocessing

For this type of waste generally, no extra packaging is considered beyond that provided during waste conditioning at the reprocessing plant.

3.3. Repository concepts for disposal of spent fuel or reprocessing wastes

3.3.1. General overview

A geological repository is generally conceived as an engineered excavation into which high-level radioactive wastes can be emplaced and sealed. The geological media and national regulations will have a significant influence on the detailed design of these excavations and the methods of sealing them to prevent the release of the wastes to the environment in concentrations that exceed regulatory limits or are potentially hazardous.

As different geological conditions exist around the world, several different media have been considered for the final disposal of spent fuel or reprocessing waste. In the countries that are contributing to this study, the following geological media are considered:

- igneous rock (Canada, Finland, France, Japan, Spain, Sweden, Switzerland, the UK and the US);
- salt (France, Germany, the Netherlands and Spain);
- clay (Belgium, France, Japan and Switzerland);
- metamorphic rock (France and Japan).

Several concepts for geological repositories have been proposed by various countries.

The tunnel-and-drift design that is used commonly in underground excavations is the primary reference configuration in most countries. This design, in which the excavated repository volume is small compared to the rock volume containing it, should provide a stable repository in all geological media being seriously considered. Other alternatives that have been considered include the emplacement of waste in large caverns that can be used for storage prior to sealing, *i.e.*, the WP-Cave concept [24]; and the emplacement of waste containers in very deep boreholes drilled into the disposal medium from the ground surface, *i.e.*, the deep borehole emplacement concept [25].

The tunnel-and-drift repository will utilise shafts or ramps, depending on the local topography and the depth of emplacement, to access the disposal level within the geological medium. The underground installations include an array of tunnels and excavated chambers that provide access to the openings in which the waste will be sealed. Equipment will be provided to excavate the openings, handle the excavated spoil, handle and emplace the waste, seal the emplacement areas and operate and maintain the openings for performance monitoring. Services, including water, compressed air, ventilation, electricity, handling and preparation of sealing materials, etc., will also be provided.

The surface facilities are an essential component of the repository and will provide for:

- the receipt of the packaged waste from the on-site packaging plant, or the receipt, inspection and acceptance of the packaged waste shipped from off-site facilities;
- the handling and management of the waste rock from the underground operations;
- the receipt, storage and preparation of the operating and sealing materials needed for the underground operation; and
- the access, security, health and safety, safeguards, management and administrative staff and systems necessary to operate the site and the repository.

Some of these functions will be shared with the packaging facilities, if these facilities are co-located with the repository. Care must be taken in economic comparisons not to duplicate the costs of the surface facilities for co-located facilities and to include these costs for each facility if they are not co-located.

The details of the design of the repository are influenced or governed by the characteristics of the geological media, the container design, the sealing system characteristics and the heat output of the waste. Each repository concept is therefore unique and comparison between them must be made very carefully.

Before the start of operation of the repository, all the surface facilities, shafts and/or ramps, underground infrastructures and at least some of the repository disposal areas will be constructed. In most concepts, the additional waste disposal areas will be constructed while waste containers are being emplaced.

The waste container will arrive at the repository from the packaging facility, sometimes in a transfer cask that will provide adequate shielding for subsequent handling. After checking for and removing any contamination, the container is brought underground through the access shaft or ramp.

The underground facilities will provide for the transfer of containers to the disposal area, emplacement of containers into prepared disposal areas and subsequent sealing of these areas along with the tunnels, shafts and ramps. Preparation systems for the sealing materials will also be provided.

If a shielding cask is used during transfer, it is removed during emplacement of the waste container and returned above ground for reuse.

In many concepts, filled tunnels and drifts will be sealed in parallel with disposal. The backfilling will be done with materials that provide adequate hydraulic strength and stability characteristics. Tunnels will be arranged to minimise the mixing of radioactive with non-radioactive operations. In some countries, *e.g.*, the USA, the tunnels and drifts will be kept open until all the wastes have been disposed of and for a certain period thereafter in order to satisfy national regulatory requirements for retrievability.

When all the waste packages have been emplaced, the remaining open tunnels and the shafts or ramps will be backfilled and sealed, and the surface facilities will be decommissioned.

In the following sub-sections, repository designs considered in OECD countries are described briefly. More details and references are given in the Countries Annex (Annex 1).

3.3.2. Repositories in igneous rock

Designs of repositories in igneous rock have been developed in Canada, Finland, France, Spain, Sweden, Switzerland, the UK and the USA. They are similar in many aspects. The waste packages are distributed in tunnels or boreholes at a minimum separation to keep the temperature rise around the containers at an acceptable level.

3.3.2.1. *Canada*

The disposal concept developed as a case study in the Canadian Nuclear Fuel Waste Management Program [16] has the repository constructed in a granite pluton. The vault is sized to hold about 140 000 spent fuel containers. It has a minimum plan area of about 2 km by 2 km and is at a depth of 1 000 m. Five vertical shafts connect the surface facilities to the disposal level.

The repository emplacement area is divided in half. Each half is operationally separated and has four panels. Container emplacement and room sealing take place in a panel on one half of the repository, while disposal rooms for future use are excavated and serviced on the other side. For transfer to the repository, the spent fuel container will be loaded into a shielding container cask that will be transferred underground and moved to a disposal room.

Vertical boreholes in the floor of the disposal room will be prepared to receive the spent fuel container. A clay-based buffer material (*i.e.*, 50 per cent sodium bentonite clay and 50 per cent silica sand, by mass) will be compacted into the borehole and a central hole will be augered in which the container will be placed. The rest of the borehole will then be filled with compacted buffer material. After all the containers are emplaced in a room, it will be backfilled with a clay-based backfill material mixture (*i.e.*, 25 per cent glacial lake clay and 75 per cent crushed granite, by mass).

3.3.2.2. *Finland and Sweden*

Repository layouts proposed in Finland and Sweden are similar. The repository will be built in crystalline rock at a depth of about 500 m (Figure 3.5). The repository consists of a series of parallel tunnels, the spacing of which is determined by temperature restrictions. The spent fuel containers are disposed in boreholes drilled into the floor of the tunnels. The Swedish concept for about 5 000 containers will occupy an area of approximately 1 km by 1 km. The Finnish concept for 1 200 containers will occupy an area of about 0.4 km by 0.9 km.

The spent fuel containers are brought down to the disposal area in a shielded elevator. At the disposal level, the containers are transferred by a shielded vehicle to the disposal area and disposed of in a borehole lined with highly compacted bentonite. After emplacement, the tunnels are backfilled with a mixture of sand and bentonite.

3.3.2.3. *France*

In the French disposal concept, the high-level waste containers will be disposed of in boreholes about 100 m deep drilled down from a drift at a depth of about 500 m. Each borehole will be 0.5 to 1.0 m in diameter to accommodate a single stack of waste packages. The drifts and boreholes will be spaced to keep the temperature rise to an acceptable level.

After emplacement of the waste, all openings will be backfilled to prevent long-term damage in the geological formations as a result of subsidence.

The repository is designed to accommodate both high-level vitrified waste and alpha-bearing waste in two separate areas. For heat-emitting alpha-bearing waste, a similar borehole design will be used, but with larger-diameter boreholes. For the non-heat-emitting alpha-bearing waste, the vault concept is envisaged. The waste is disposed of in vertical pits in a concrete structure in the lower part of the vault.

A similar design is also used for a repository in schist.

3.3.2.4. *Spain*

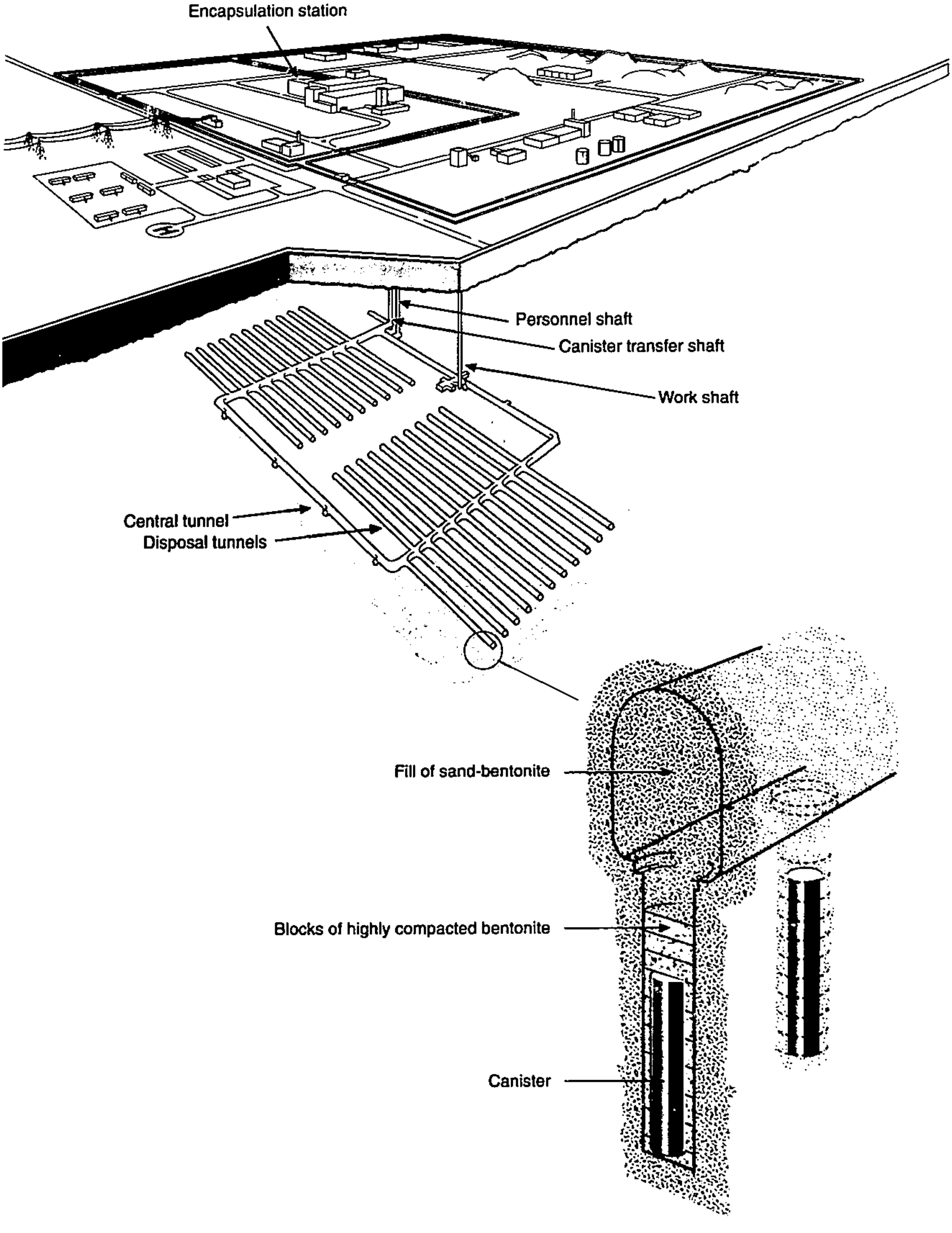
The preliminary conceptual design performed in Spain assumes a repository built in granite rock at a depth of about 500 m. The repository consists of parallel disposal galleries, with corresponding transport tunnels and service areas. Access to the repository will be via a ramp.

The emplacement mode will be drift emplacement of steel containers with compacted bentonite to be used as buffer material. After emplacement of the waste, all remaining openings will be backfilled with a mixture of sand and bentonite.

3.3.2.5. *Switzerland*

In the Swiss disposal concept described in Project Gewähr [22], about 6 000 self-shielding overpacks containing vitrified waste will be emplaced in the crystalline rock of northern Switzerland. The disposal will take place at about 1 200 m depth. The repository area will be reached by two vertical shafts for waste handling and rock handling.

Figure 3.5 **Encapsulation and final disposal facilities for spent nuclear fuel (Finnish concept)**



The underground areas will consist of two large caverns for the underground infrastructure and a network of tunnels. The tunnels will have a circular profile and will be excavated by a tunnel-boring machine. The waste packages will be emplaced at the centre of the tunnels at regular intervals and the remaining space in the tunnel will be sealed with bentonite backfill.

In a separate area of the repository, alpha-bearing waste will be disposed of in concrete silos surrounded by a layer of bentonite.

3.3.2.6. United Kingdom

For the cost study made in the United Kingdom, the assumed repository concept includes a host geology of unfractured granite with disposal at about 1 000 m below the surface. Of the roughly 15 000 canisters assumed to be disposed of, the majority contain vitrified high-level waste (VHLW), and a few others contain spent fuel for direct disposal. All canisters are assumed to be in a mild steel overpack 65 mm thick.

The repository surface facilities will be connected to the disposal level by two shafts, the main one 8 m in diameter for HLW lowering and mine spoil hoisting, and the smaller one 6 m in diameter for services and personnel access. The disposal level will comprise four parallel "spine" tunnels and an access tunnel effectively marking the rectangular periphery of the disposal area. The 15 pairs of 975-m-long disposal tunnels will run out from the spine to the peripheral access tunnel. The overpacked waste will be stacked 20 units together in a 30-m-deep borehole that has been drilled vertically down into the tunnel floor. Disposal tunnels will be sealed with cementitious grout and backfilled with concrete.

3.3.2.7. United States

For costing purposes, the US disposal concept assumes that the candidate repository site is at the Yucca Mountain in Nevada. The underground repository would be constructed at a depth of about 300 m in a tuff horizon located above the water table. The underground facilities consist of a series of emplacement panels. The waste containers will be disposed in boreholes drilled into the floor of the emplacement panels. To protect the container, the borehole is lined with a metal casing and after disposal the hole is sealed with a thick metal plug for radiation shielding.

The underground area is reached by two ramps and a number of shafts. The ramps will be used for waste and rock transport, while the shafts will be used for ventilation and personnel transport.

The tunnels will be kept open during the full operational phase and during a certain period after operation. After this period, the emplacement areas will be backfilled with crushed tuff.

3.3.2.8. Japan

Japan has studied a repository design for igneous rocks. Consideration is being given to placing self-shielding overpacks containing high-level vitrified waste and bentonite buffer material in the boreholes or at the centre of the tunnels at regular intervals. A similar design is also considered for sedimentary rocks.

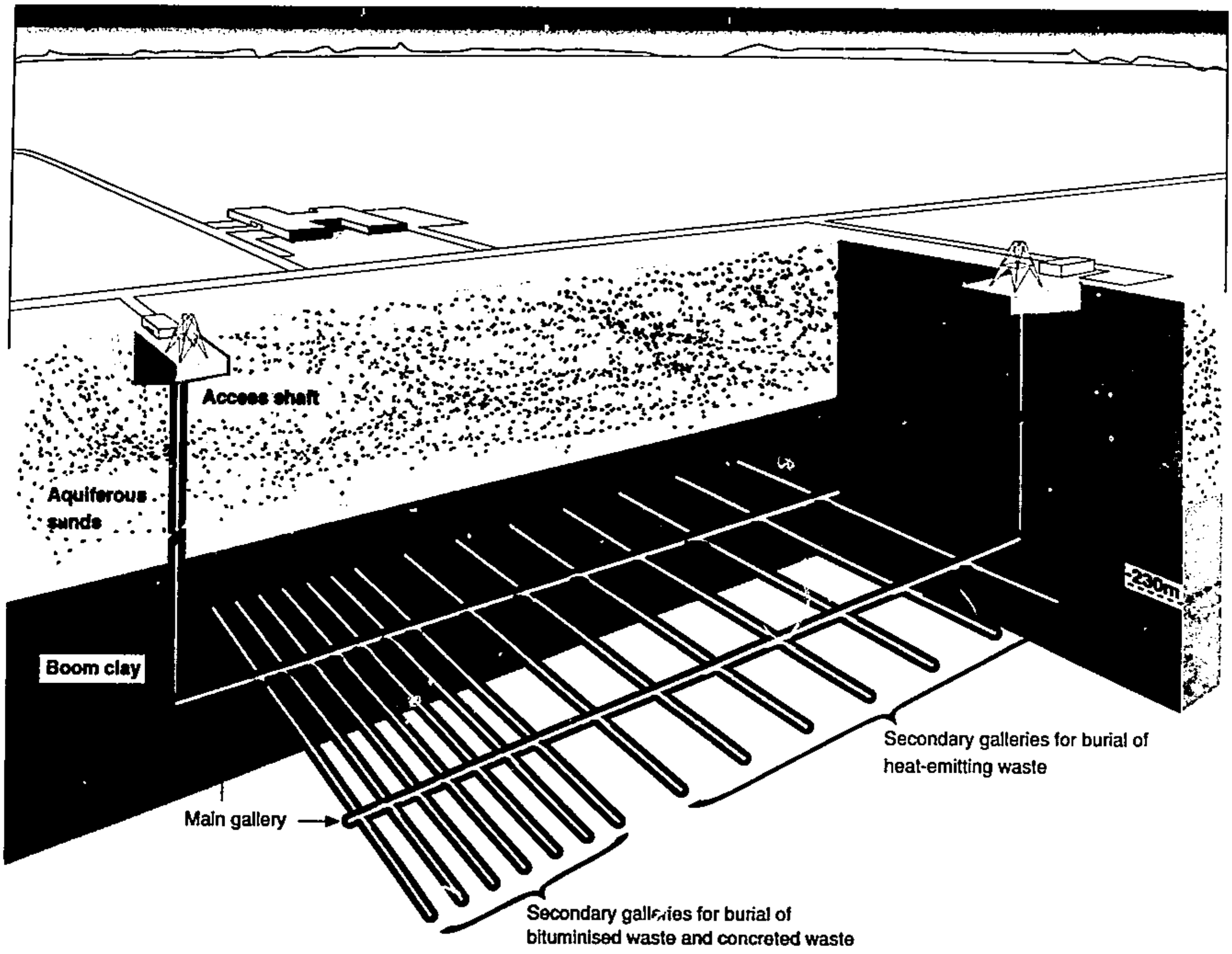
3.3.3. Repositories in clay

Designs of repositories in clay have been studied in France, Belgium and Switzerland [26]. The French design is based on deep borehole emplacement from tunnels similar to the French concept for the igneous rock repository, but with dimensions adapted to the softer clay rock. For example, long boreholes are used for alpha-bearing waste rather than the vault concept. The Swiss design is also similar to the one described above for igneous rock. The Belgian design is described in some detail below.

The Belgian repository is planned to be built in the Boom clay formation in the neighbourhood of the Mol-Dessel site. It will be used to dispose of high-level vitrified wastes and intermediate-level alpha-bearing wastes.

The waste disposal facilities will comprise surface installations, access shafts and a network of underground galleries. The repository disposal level will be 180 m to 270 m below ground, as shown in Figure 3.6. The surface installations will include facilities for waste acceptance and inspection, buffer storage areas and the servicing of the shafts and underground operations. There will be one main access shaft, about 6 m in diameter and 250 m deep. In addition, there will be at least two secondary shafts, each giving access to a separate operating region of the repository.

Figure 3.6 **Artist's view of Belgian repository (axial concept)**



The underground network of galleries will be located at mid-height in the Boom clay formation. Main galleries about 3.5 m in useful diameter will be utilised for waste package transport and handling. Disposal galleries about 2 m in useful diameter will be excavated perpendicular to the main galleries and will be the location where the waste packages will be buried. The galleries will have a circular cross section and will be lined with concrete blocks.

The vitrified waste packages will be placed centrally in the galleries. For the emplacement, a transfer cask will be used. The void around the packages will be backfilled, a clay-based mixture being one of the options. The distance between the secondary galleries for the vitrified waste will be about 50 m to allow for heat dissipation.

The non-heat-generating alpha-bearing waste packages will be stacked as efficiently as possible in the galleries. The void space between the packages will be backfilled. The distance between these galleries will be set by the requirements of excavation and operation.

The main galleries will remain open throughout the waste burial operations. At the end of operations, the services will be removed, the main galleries will be filled with suitable backfill material, and the shafts will be dismantled and sealed.

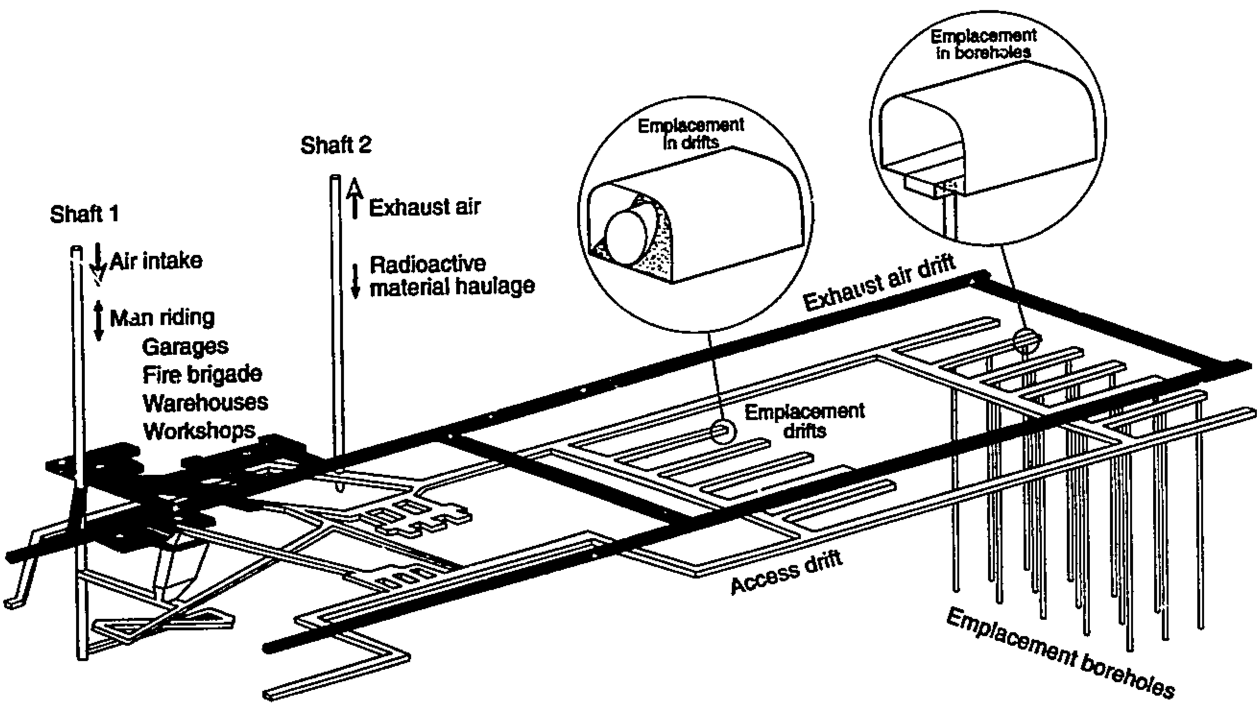
3.3.4. Repositories in salt

Designs of repositories in salt have been studied in Germany, the Netherlands, Spain and France. Only the German, Dutch and Spanish designs are described here.

3.3.4.1. Germany

The repository for spent fuel, vitrified waste and other heat-generating waste from reprocessing is planned to be built at a depth of 870 m in the Gorleben salt dome. The repository consists of a central infrastructure section and an emplacement section located between two parallel access drifts (see Figure 3.7). Two shafts are required for the mining and emplacement activities.

Figure 3.7 **Schematic layout of a repository for borehole and drift emplacement in salt formation (Germany)**



The design of the repository will ensure that the temperature will not exceed 200°C at the surface of any canister. Different types of emplacement drifts will be utilised. Canisters with high-level vitrified waste and other heat-generating wastes will be disposed of in boreholes 300 to 600 m deep drilled in the bottom of drifts. Shielded POLLUX-type casks containing spent fuel will be disposed of horizontally in the drifts.

The distance between the emplacement holes and between the drifts is determined by the temperature limitation. The drifts and boreholes will be backfilled with crushed salt shortly after the waste package is emplaced.

Excavation will be performed as emplacement proceeds. Conventional drilling and tunneling techniques will be utilised. The emplacement, backfilling and sealing activities can always be physically separated from the excavation activities.

3.3.4.2. The Netherlands

In a feasibility study performed in the Netherlands, different concepts for disposal in a salt dome, a salt pillow and a bedded salt structure have been studied [27]. Both conventional mining techniques with shafts and galleries and deep boreholes drilled from the surface have been studied.

The shaft and gallery designs are similar to the German design described above, with borehole disposal from the floor of the gallery. For the deep borehole design, the vitrified waste packages are lowered into the salt directly from the surface, and holes are then plugged.

3.3.4.3. Spain

A preliminary conceptual design study performed in Spain assumes a repository at about 800 m depth. The design is similar to that for granite and includes parallel deposition galleries, transport tunnels and service areas. The waste containers will be emplaced horizontally in the galleries. However, the repository area will be reached by a shaft. The buffer material will be excavated salt rock. After emplacement of the waste, all remaining openings will be backfilled with salt concrete.

Chapter 4

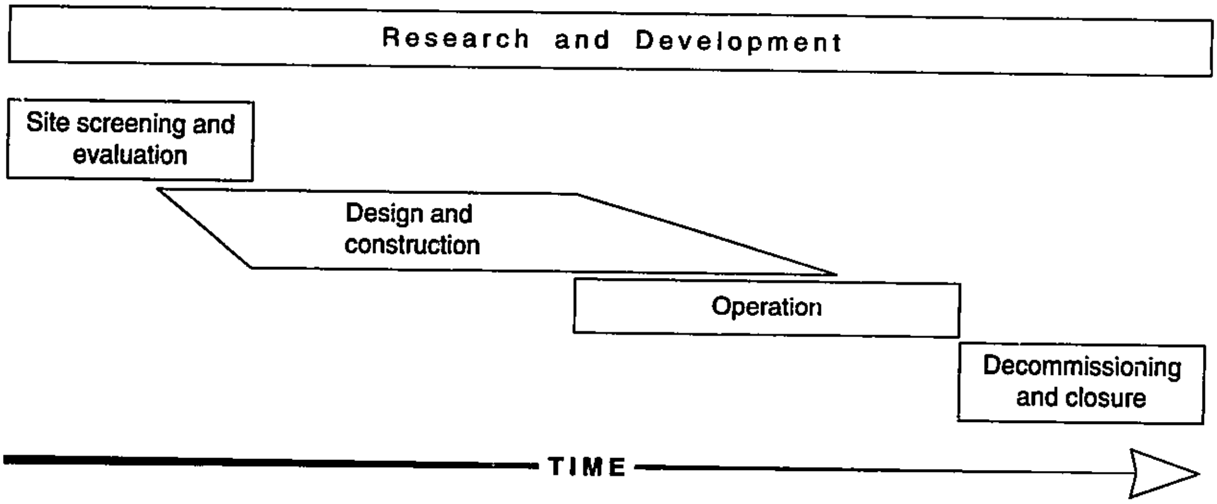
COST COMPONENTS

4.1. Introduction

To compare the estimated costs of disposal systems fairly, each estimate must include all the costs of facilities and operations to package and dispose of either spent fuel or reprocessing wastes.

The cost of a disposal system can be divided into several stages. These stages include specific activities and facilities that will result in a functional system. They are shown chronologically in Figure 4.1. The cost estimates provided by the contributing countries are included in the Countries Annex (Annex 1). In the body of the report, the costs for design and construction, operation, decommissioning and closure are considered comparatively, while the costs for research and development (R&D), and site screening and evaluation are tabulated for information.

Figure 4.1 **Stages in encapsulation and disposal**



4.2. Cost elements for packaging and disposal strategies

4.2.1. Research and development

Each national disposal programme includes research and development (R&D) studying important issues and questions. Many of these have been completely or partially resolved. Those remaining will be studied in current or future R&D programmes. These studies have required and still require facilities such as surface and underground laboratories with specialised equipment to study the various components of the disposal system.

Many of the issues are not wholly technical, containing significant elements of social and political concern, and research in these areas is included in many programmes.

The issues, questions and uncertainties in a general sense are similar in all countries but the details vary with the geological medium, the national energy strategy and the governing regulations. The definitions of the R&D costs to be included in the cost estimates vary significantly from country to country. Therefore, the comparison of the supporting R&D programmes as an element of the disposal system cost is not practical.

4.2.2. Site screening and evaluation

Siting is the identification of potential disposal sites (site screening) followed by detailed investigation at one or more preferred sites (site evaluation).

Site screening is the identification of a small number of potential areas or sites that may be technically suitable and acceptable to the public for the safe disposal of nuclear fuel waste and that warrant the expenditure of resources for detailed investigation. By a process of elimination, regions will be screened on the basis of exclusion criteria, which take into account factors such as: stability and seismic risk; potential for mineral resources and alternate use; geological setting; hydrological setting; environmental sensitivity; and socioeconomic impacts. Sites with a high technical ranking and high sociopolitical acceptance will be recommended for detailed evaluation.

During the site screening stage, conceptual designs for the packaging and repository facilities will be completed to be used for developing cost plans and as a factor in considering the relative merits of sites.

The economics of this stage of the disposal system development will be very difficult to compare between countries because they may be dominated not by the technical aspects but by the social, regulatory and political aspects of the siting process. These will differ radically between countries, depending on the review and approval process. In some countries, many potential sites must be compared and in other countries it may be sufficient to show that one site is suitable. In later phases of the disposal system development, these aspects are still present but are likely to be small relative to the technical/engineering costs of the disposal system.

Site evaluation is the detailed investigation of the surface and subsurface conditions at one or more potential disposal sites. It provides the technical information needed to design the disposal vault and to assess the disposal system performance and impact at each site. Site evaluation begins with surface-based characterisation to outline the geological, mechanical, hydrogeological, geochemical and environmental conditions. It includes exploratory borehole drilling, and monitoring to extend the knowledge in detail, to depths beyond that planned for the repository. At preferred sites, underground characterisation consisting of exploratory excavations (such as shafts to and tunnels through the proposed repository horizon) will be performed to provide further detailed information on the geological environment. These data will confirm and extend the characterisation knowledge base developed from the surface studies. In addition, the excavation process will provide initial observational information on the mechanical and hydrogeological responses to a disturbance of the site.

4.2.3. Design and construction

Based on the results of the site evaluation, detailed designs for the packaging and surface facilities and detailed preliminary designs of the repository underground facilities will be completed. The information from the site evaluation and laboratory/in-situ testing programmes, the packaging facility designs and the repository designs will be the basis for a disposal system performance assessment. The safety of the facilities will be assessed for the preclosure or operating period and for the post-closure phase. These assessments will be used as a basis for the construction license application to the national and local authorities.

Owing to the uncertainty in the geological environment, it is likely that design adjustments will be necessary for the underground facilities as information is gathered from additional characterisation activities during construction and operation. These design changes are not expected to be significant and the design will be adjusted until the activities that expose new disposal areas or perturb the underground environment are completed.

Construction is the planned execution of a series of steps that will create and make operational the packaging plant and repository, the ancillary service facilities, utilities and infrastructure. Construction activities will focus on one site for a co-located packaging plant and repository, and will be on two sites for separate packaging and repository facilities.

All the surface facilities, surface infrastructure, shafts and/or ramps, underground infrastructure and at least some of the repository disposal areas will be constructed before the first waste shipment is received. In most concepts, additional waste emplacement areas will also be constructed concurrently with the emplacement of waste.

4.2.4. Operation

"Operation" is the packaging and disposal of spent fuel or reprocessing wastes. It consists of receiving either spent fuel assemblies in transport casks and possibly packaging them in disposal containers or reprocessing wastes from a reprocessing plant and accepting them for disposal as delivered or overpacking them in another disposal container. The disposal containers are transferred to the repository and sealed in a disposal area. When a disposal area is filled, it is backfilled and sealed according to national requirements.

Excavation and preparation of additional disposal areas may continue concurrently with disposal operations. During this time, technical studies of the newly exposed geological medium will continue to improve understanding of the site. Environmental and repository performance monitoring will also continue to measure any effects due to operation of the packaging plant and the repository.

4.2.5. Decommissioning and closure

Decommissioning and closure are the orderly decontamination, dismantling and removal of surface and subsurface facilities, and the backfilling and sealing of tunnels, shafts, service areas, and exploratory and monitoring boreholes throughout the repository and its site. A packaging plant at a separate location would be subject to its own decommissioning programme. Final closure will be completed when all facilities, monitoring systems and installations are removed and all openings are sealed.

The requirement for safeguards on the final disposal of spent fuel will be a factor in repository decommissioning and closure. The IAEA has a programme under way to address this issue and its recommendations may guide the national regulatory bodies on setting the safeguard requirements for sealed repositories [28].

Extended monitoring is an optional stage that may be required either immediately before or following the backfilling and sealing of the repository and before approval is given for final closure and decommissioning. This stage would delay decommissioning until sufficient data had been collected.

The surface of the site would be returned to a state suitable for public use. There may be restrictions on the use of the subsurface to reduce the probability of inadvertent human intrusion into the repository. In addition, postclosure monitoring may be desired by the regulators and public, and could continue as long as there is institutional control of the site.

4.3. Structuring of cost estimates to facilitate comparison amongst different estimates

From the above description, it is obvious that cost estimates could be structured in many different ways and that a number of items may be included or excluded, depending on the purpose for which the estimate is prepared and the estimating strategy assumed.

The purpose of this report is to discuss the variation in the technical costs of packaging and disposal of spent fuel or reprocessing wastes, and thus only the portions of the cost estimates least influenced by non-technical factors are compared. It is recognised that those elements of costs that are excluded are the true costs of implementing spent fuel management and therefore must be included in the analysis of a national disposal strategy.

The elements of costs that will be included and excluded from the comparative discussion in this report are listed in Table 4.1.

Table 4.1. **Recommended coverage of comparison of disposal system cost estimates**

Cost Element	Packaging Plant	Repository	Surface Facilities
Research and development	no	no	no
Site screening and evaluation	no	no	no
Design and construction	yes	yes	yes
Operation	yes	yes	yes
Decommissioning and closure	yes	yes	yes

Chapter 5

METHODS OF COST CALCULATIONS

5.1. Cost calculation procedures

Some of the activities and facilities employed in the final disposal of spent fuel and/or reprocessing wastes are new and have not yet been tested. However, the costs for these activities can be calculated using the cost-estimating methods normally applied in technical projects. The new activities or facilities are divided into components that are known and for which cost estimates can be prepared. With this approach, there will be only a few components that are new and for which analogues are not available. The cost estimates of these components must be based on expert opinion. In consideration of the increased uncertainties in the cost estimates for a new system, greater contingencies are included in the estimates.

As can be seen from Annex 1, cost estimates for final disposal have been performed or are under way in many countries that have a nuclear power programme. The methods applied are similar and consist of the five following steps:

- define the scope of the system, *e.g.*, the amount of fuel or waste arising, and the activities, equipment, processes and facilities for which cost estimates should be included in the calculation of the total cost;
- describe the facilities and the work activities during construction, operation, sealing and decommissioning to the level of detail that will provide the necessary information for the estimate;
- estimate, in constant-money value, the time-distributed costs of the activities, equipment, processes and facilities, and combine these into a total cost;
- define the uncertainties and the need for contingencies and risk factors by item, by major elements of the cost estimate, or by total project cost, and add these to the time-distributed costs;
- apply the financial analysis method appropriate for the end use of the cost calculation, *e.g.*, present value of required funds, funds invested at a real interest rate, etc.

In general, all cost estimates will follow the steps listed above to the end of the fourth step. The action taken in the fifth step, the application of the financial analysis to prepare a cost calculation, will depend on the final use of the cost information. It may be that more than one financial analysis method will be applied to the same constant-currency, time-distributed cost estimate because the information may be used in many ways within a single country.

5.1.1. Scope of the system

The first step in preparing a cost estimate is to define the arisings (mass) of spent fuel and/or reprocessing wastes, and the characteristics of these products, *e.g.*, size, weight, radiation field and heat emission. The results are dependent on the number and type of reactors (existing and planned) in the country, the fuel burnup, the strategy for spent fuel management (*i.e.*, reprocessing or direct disposal approach) and the time schedule for the disposal.

The total system for the management of the spent fuel comprises a number of activities, as discussed in Chapter 2. In this report, only the costs for packaging the waste, if necessary, before disposal and the actual disposal costs are considered in a comparative way. Cost estimates for other elements of the nuclear fuel cycle are given for some countries in the Countries Annex (Annex 1).

5.1.2. Description of facilities and activities involved

The bases for the cost estimates are usually functional descriptions for each facility and all activities involved. These descriptions include layout drawings, equipment lists, operational procedures, personnel forecasts, etc.

The level of detail in these descriptions is dependent on the purpose of the cost estimate and the maturity of the studies of the final disposal system. As with any other cost estimate, there will also be a balance between the level of detail in the calculation and the cost allowances added for work not specifically defined in the estimate.

5.1.3. Cost estimates

Normally, the costs are calculated separately for a number of items, such as construction, operation, decommissioning and sealing. As not all the information is available at the time of calculating the cost, the calculations are often performed stepwise. Initially, a base cost estimate is calculated that includes:

- Quantity-related costs that can be calculated directly from the design specifications and drawings using unit prices, *e.g.*, for concrete casting, rock excavation and operating personnel.
- Non-quantity-related cost items for which details are not included in the drawings at this stage but that will be included when detailed construction drawings are made. Examples of such costs are control equipment for pumps and valves, small piping, fixtures in the concrete etc. These costs can be estimated fairly accurately from experience from similar work.
- Secondary costs for administration, engineering, purchasing and inspection, as well as costs for temporary buildings, machines, housing, canteens, offices, etc. These costs could either be calculated in a detailed way or be included as a factor derived from previous experience from similar work.

5.1.4. Contingencies and risk factors

On top of the base cost estimate determined from known information a contingency allowance is added to find the total cost. The contingency is an allowance for smaller elements and activities that have not been estimated in detail but are a necessary part of the project, and for the general degree of uncertainty associated with the details of the project, the unit costs and the cost factors applied to the project. The size of the contingency will depend on a number of factors, including the level of detail and knowledge about the facility and/or process studied, experience from similar work, the R&D work needed before the design is finalised and the purpose of the cost estimate. The last factor is particularly important because it defines whether the cost estimate should be a best estimate of the costs or a conservative value. The latter could be the case when the cost calculations are used as a basis for determining a fee to be charged for disposal, as required by law or regulation in many countries.

The contingencies are generally assigned as a percentage of the item costs with due regard to the complexity of the different items, which means that different contingencies can be applied for different items. The percentage is based on previous experience with similar items and the level of detail in the basis of the estimate.

As the packaging and final disposal system will be a first-of-its-kind operation, it will normally be prudent to add some extra allowance for unforeseen costs. This could be done by an added contingency on the individual items of the estimate or as an extra contingency on the total project cost estimate.

In the costs reported in the Countries Annex, the magnitude of the contingency applied varies with the different countries. The variation is between 15 and 50 per cent and does not necessarily reflect a difference in prudence between the countries but rather the difference in the level of detail used to calculate the base cost estimate and the different purposes for the estimated project cost.

Another approach to the application of a contingency involves combining it with the determination of risk factors. For this type of analysis, a reasonably detailed cost model is necessary that can be applied to assess the change in costs due to changes in the assumptions for the packaging and disposal system. In this way, a series of cost estimates is determined that can be used to select the appropriate risk factor to be applied to the project cost so that a sufficient allowance for uncertainties is provided in the final estimated costs.

A risk factor may be included in cost estimates to allow for non-technical factors that may have a significant direct impact on the cost of the project. Two very important examples are allowances to account for social/political and/or economic uncertainty in the implementation of disposal that could change the project design or schedule. An example of a social/political issue that would affect the cost of a project is a process for project review and licensing that delays or extends the schedule and thereby requires additional funds to maintain and support the project organisation. An example of an economic factor that would affect cost is a recession that reduces electricity demand and therefore reduces the funding that is accumulating to pay for packaging and disposal.

Another factor that may have an important influence on the total cost of the project is the evolution of technology. Significant advances in technology in any area may result in modifications to the design and operation of the facility and to the design and construction of the disposal system. These could affect the labour and material requirements, the project schedule and, therefore, the overall project cost. Although technological evolution would normally be expected to reduce project cost, the effect may in fact be an increase or decrease.

In some national programmes, risk factors are included in the cost estimates to account for these uncertainties. In other programmes, these risks are recognised but not quantified. In such programmes, cost increases will be dealt with as they occur. To some extent, the decision to include risk factors will depend on the purpose of the cost estimate.

5.1.5. Financial calculations

The last step in completing the cost calculation process is to do a financial calculation on the constant-currency, time-distributed cost estimate. As the time schedules considered for spent fuel management are extremely long, in most cases 50 to 100 years, the timing of the expenditures will have a strong impact on the results of the financial calculation.

The type of financial calculations performed on the constant-currency, time-distributed cost estimates include the following examples:

a) Calculate the costs in the currency of the day. That is, calculate the costs (including contingencies) in each year of an assumed project schedule assuming a rate of inflation for materials, equipment, labour and services in the year of use.

b) Calculate the present value of the costs determined in a) assuming a rate of return on money invested in other activities (such as in governmental security bonds).

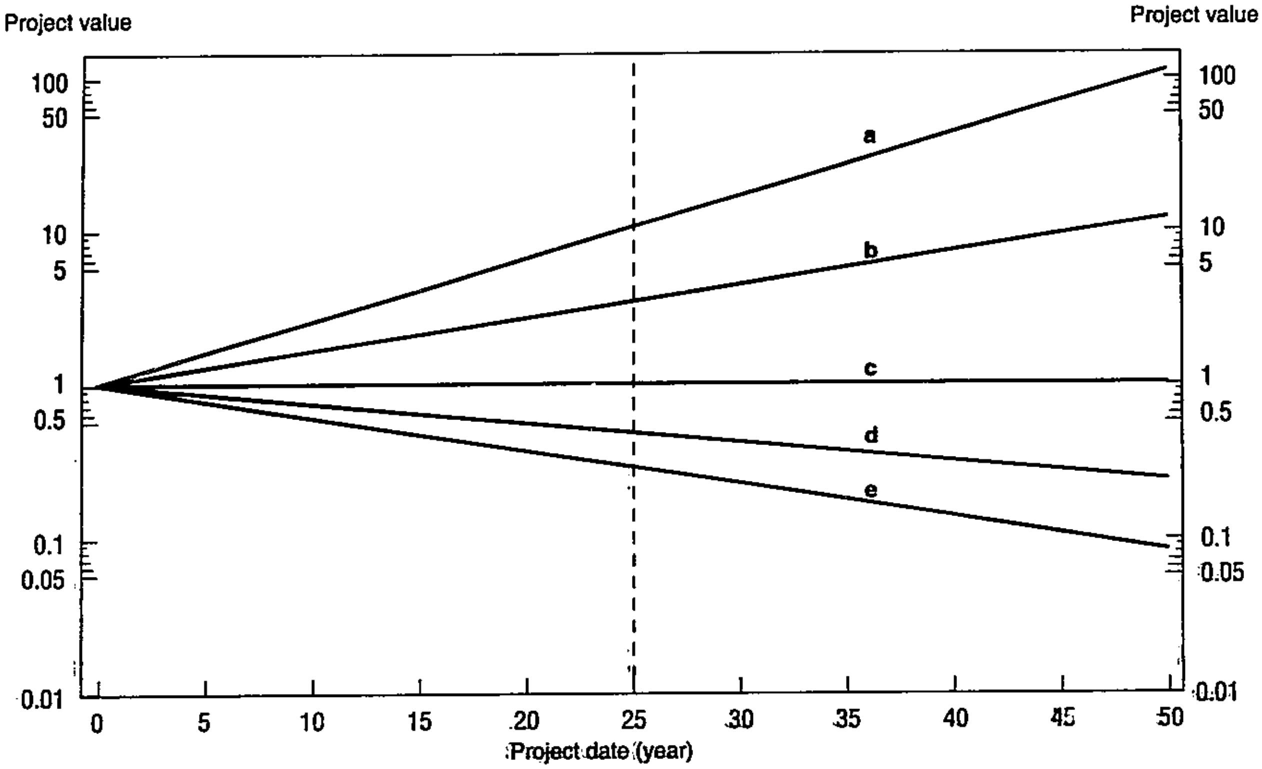
c) Calculate the levelised unit costs. That is, calculate the net present value of services, such as waste disposal and electricity generated, according to the methodology described in a) and b), and then obtain the levelised unit costs by dividing the present value of the costs by the present value of services, *i.e.*, cost per waste package disposed of. Levelisation and discounting are discussed in an NEA report [1].

The particular type of financial calculation performed will depend on the end use of the information. For example, calculation *a)* would be done to show the projected actual expenditures as they would appear in the project accounts, calculation *b)* would be done to establish the funds that must be collected over the period of reactor operation to pay for disposal, and calculation *c)* would be done to determine the charges to the electricity users in order to collect enough money to pay for the project.

The effect of the assumptions made in these cost calculations on the resulting cost estimate is illustrated in Figure 5.1. In this figure, the effect of the inflation rate assumption and the real interest rate assumption are shown. A further example of this effect is shown in Table 5.1 for cost calculations done on the Swedish cost estimate indicated in Figure 5.2, assuming various inflation and real interest rates. The resulting cost can vary over a wide range because of the assumptions made on inflation rate, interest rate and project schedule. In the example given in Table 5.1, the cost information for the project varies by a factor of more than 300 between the costs presented in the currency of the day (10 per cent inflation rate) and the discounted costs (5 per cent real rate of interest).

In most countries, the task of disposal is entrusted to a separate agency or company. This agency is government-controlled in some countries and privately owned in others. The way in which the agency is organised and financed could have an impact on the calculated costs for disposal. The disposal agency may be established as a non-profit organisation or a profit-making organisation. In the latter case, a profit margin has to be added to the cost estimates and included in the cost calculations and financing plans. Either the financing will come from established funds that are utilised when the costs appear, or the agency can charge its customers when the disposal services are rendered. In the latter case, the agency is obliged to borrow money for the investments and will thus have to include a financing cost in its cost estimates and in its fees for the services. In the former case, while no financing costs are explicitly included, there will be implicit "financing costs", as the funds will be spent earlier and thus will earn less interest.

Figure 5.1 **Effect of inflation and real rate on a one-year project of value = 1**



a) Inflated project value in the currency of the year assuming an inflation rate of 10% per year.
b) Inflated project value in the currency of the year assuming an inflation rate of 5% per year.
c) Inflated project value in the currency of the year assuming an inflation rate of 0% per year, present value of a future project in present currency (year 0) assuming real interest rate of 0% per year or project value in constant money value of the present (year 0).
d) Present value of a future project in present currency (year 0) assuming real interest rate of 2.5% per year.
e) Present value of a future project in present currency (year 0) assuming real interest rate of 5% per year.

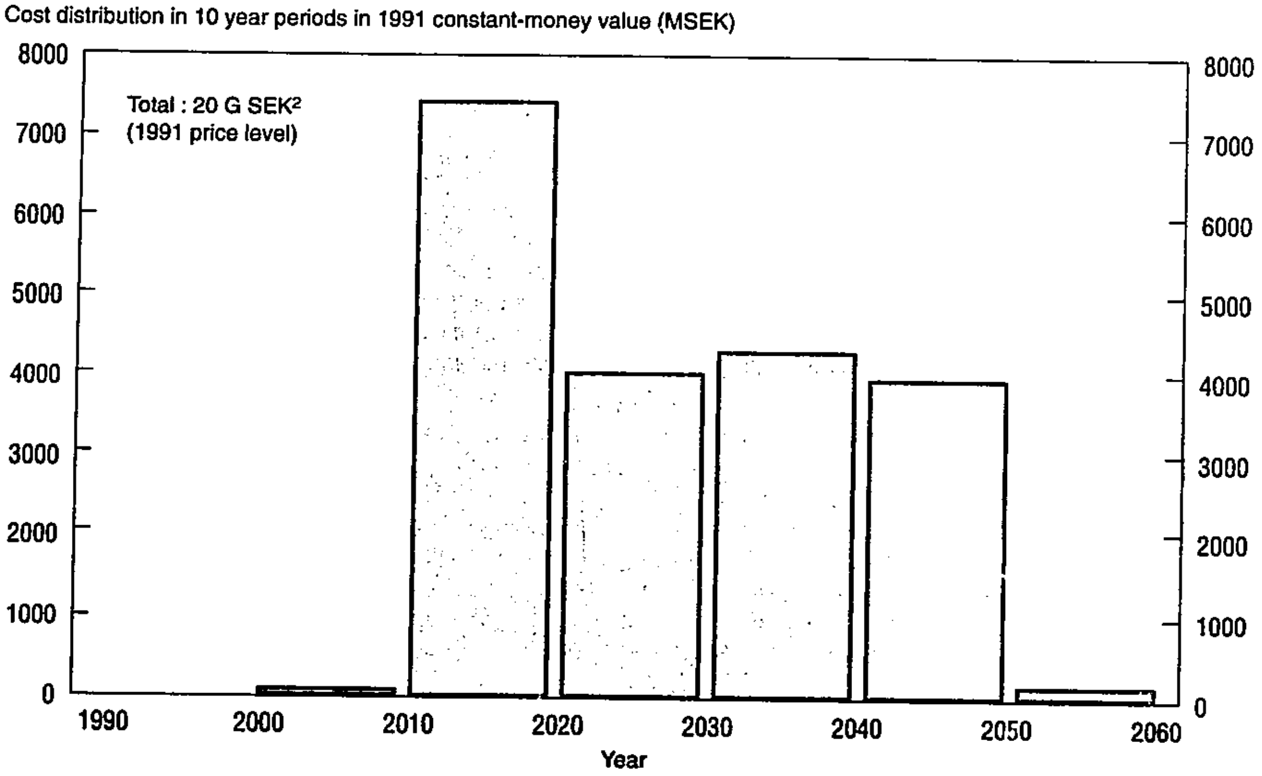
Table 5.1. **Example of the effect of inflation and real interest rate assumptions on the results of cost calculations**

The cost distribution in Figure 5.2 is used as a reference case

Assumptions	Total project value[a]
1991 Price level	20 G SEK
Inflation (5%)[b]	150 G SEK
Inflation (10%)[b]	1 300 G SEK
Discounted (2.5%)[c]	8 G SEK
Discounted (5%)[c]	4 G SEK

a) G SEK is a thousand million Swedish Krona.
b) Nominal costs calculated by assuming an annual inflation rate of 5 or 10%.
c) Costs discounted back to the year 1990 with an annual discount rate of 2.5 or 5%.

Figure 5.2 **Typical cost distribution of a disposal project[1] in a constant-money value**



1) The Swedish cost estimates, which are included in the Countries Annex, are used as an example.
2) SEK : Swedish Krona.

From the national programme descriptions in the Countries Annex (Annex 1), it can be seen that many countries have developed methods for funding the future costs of waste disposal. Generally, the costs are to be covered by a fee included in the charges for electricity generated by nuclear reactors, or by a prorated fee charged on all electricity sold by the producer. Control of these funds varies depending on the country and some examples follow:

- control by a government authority and the accumulating funds earn interest through investment;
- control by the agency responsible for waste disposal and the funds earn interest normally;
- control by the electrical utility and the funds may or may not earn interest through investment;
- control by the electrical utility and the funds are used to reduce current borrowing requirements.

The use of these funds may also vary among countries. In some cases, the funds pay for all development as well as actual waste disposal (*e.g.*, USA and Sweden) and in others only a portion or none of the R&D is funded (*e.g.*, Canada).

5.2. Relevant experience of cost data from other areas

Although the packaging and disposal of spent fuel or reprocessing waste are new activities that have not yet been carried out anywhere in the world, the basic components involved in the process are often well understood because there are similar applications in other areas of the nuclear fuel cycle or in other industries. The experience gained from the construction and operation of nuclear power plants, reprocessing plants, interim storage facilities and low- and intermediate-level waste disposal facilities is relevant for parts of the spent fuel or reprocessing waste disposal systems.

A packaging or waste-receiving facility for spent fuel, for example, will include some or all of the following: a reception facility for spent fuel transport casks, a buffer storage pool, transfer machines for spent fuel and disposal containers, and hot cells for the actual packaging. Reception facilities for spent fuel transport casks and storage pools have been in operation for many years at the reprocessing plants and interim storage facilities, and a good understanding of the costs exist. Transfer machines for spent fuel and casks are also used at these facilities. The new part of the packaging facility is the actual packaging subsystem. Although this can be broken down into smaller elements of proven technology as a basis for estimation, the uncertainty will be higher because the elements still have to be assembled and tested together in the new application.

For the actual disposal facility, the important cost data are for rock excavation, underground service installation, rock drilling and engineered barrier preparation and installation. Here, experience from the underground construction industry and from the use of underground facilities for storage (oil, gas, etc.), underground offices and fortifications is very valuable for some aspects of the cost estimating. In other areas, however, there is limited knowledge of the processes, or no relevant experience. In these cases, the costs have more uncertainty and this must be accommodated by applying appropriate contingency allowances.

Chapter 6

COMPARISON OF COST ESTIMATES

6.1. Cost estimates provided for this study

For the purpose of this study, the countries represented in the Expert Group were requested to provide information on recent cost estimates for the deep geological disposal of spent fuel and reprocessing wastes. Twelve cost estimates were obtained from eleven OECD countries. In the case of countries such as France and the Netherlands, which have several cost estimates for different waste amounts or different geological media, a reference estimate was selected for the purpose of this chapter, while Spain provided two cost estimates, one for granite and one for salt rocks. Of the resultant 12 estimates, 5 estimates are for direct disposal of spent fuel and 4 estimates are for disposal of reprocessing wastes. Among the other 3 estimates, which assume the disposal of a mixture of spent fuel and reprocessing wastes in a single repository, 2 estimates (the British and the US estimates) assume a considerable amount of one of the wastes and a much smaller amount of the other. They are classified under one of the disposal scenarios, depending on the main waste. The German estimate is based on a mixture of considerable amounts of both wastes and thus is included in both analyses for the two disposal approaches.

The cost estimates are presented in the Countries Annex (Annex 1) and are summarised in Table 6.1 for disposal of spent fuel and in Table 6.2 for disposal of reprocessing waste. The results are presented in two tables, as the costs for direct disposal of spent fuel should not be compared with the costs for disposal of reprocessing wastes, since the cost estimates do not include all steps of fuel management.

It should be noted that the cost estimates included in Tables 6.1 and 6.2 represent costs for the selected parts of the waste system shown in Table 4.1, namely the direct costs associated with waste packaging and disposal. Therefore, the cost estimates do not include the costs of R&D, site screening and evaluation, and waste transportation outside the repository site; thus the cost figure may be different from the cost estimates described in the Countries Annex.

The first two columns of the tables show the amount of uranium assumed in the disposal programme and the corresponding electricity generation. In the third column, the volume of waste to be disposed of is given. The waste volumes include any canisters and overpacks used. In the case of reprocessing waste, the volumes of both high-level waste and alpha-bearing waste are given.

The fourth column, "Packaging", gives information about the container used for the spent fuel or high-level waste and whether separate packaging is included in the estimate. The fifth column, "Characteristics of the repository", has five sub-columns; depth, host rock, volume of excavated rock, operating period and sealing material. "Depth" is the depth of the underground repository from the ground level. "Host rock" is the kind of rock in which the repository will be constructed. When different geological media are considered in a cost estimate, as in the case of the French estimate, no host rock is indicated. The next sub-column provides the volume of rock excavated for construction of the repository. "Operating period" is defined here as the period between the start and the end of waste emplacement. The final sub-column describes the material assumed to be used for sealing and backfilling the repository.

In the final column, the cost estimates are first shown in the original form in which the Expert Group received them. The number in parentheses under the currency unit indicates the base year for the money value. Then the original cost figures are converted to US dollars of July 1991 and shown in the second-last sub-column. It should be noted that all cost figures are presented without discounting.

The conversion to US dollars has been done by the NEA Secretariat. Firstly, the estimates have been changed to correspond with the same base year and month, July 1991. For this conversion, the Consumer Price Index (CPI) ratio between time of estimate and July 1991 was used. Secondly, the modified estimates have been converted to US dollars using the actual exchange rates between the dollar and other national currencies as of July 1991.

Table 6.1. Recent cost estimates for packaging and geological disposal (for disposal of spent fuel)

Country	Spent fuel[a] (tU)	Corresponding electricity generation (TWh)	Volume of waste[b] (m³)	Packaging[c] (for spent fuel)		Characteristics of the repository					Estimated costs[d]		
				Inclusion of packaging cost	Container (thickness)	Depth (m)	Host rock	Volume of excavated rock (M m³)	Operating period (year)	Sealing material	In national currency unit (the year of money value)	in billions of US$ of July 1991	Proportion[e] of the underground costs to the total cost estimates (%)
Canada	191 000	10 900	99 000	Yes	Titanium (6.3 mm)	1 000	Crystalline rock	7.2	41	Bentonite and sand	9500 M C$ (1990)	8.7	46
Finland	1 840	430	2 600	Yes	Copper-steel (10 cm)	500	Crystalline rock	0.24	20	Bentonite and sand	3.2 b Mk (end of 1990)	0.76	39
Germany[f]	35 600	8 340	96 000	Yes	Stainless steel (15 cm)	870	Salt	2.5	50	Excavated rock	7500 M DM (1988)	4.6	42
Spain[g]	6 740	1 900	40 000	Yes	Steel	800	Salt	1.3	25	Excavated rock	260 b Ptas (1991)	2.4	27
[h]				Yes	Steel	500	Granite	0.6	25	Bentonite and sand	220 b Ptas (1991)	2.0	42
Sweden	7 840	2 000	12 900	Yes	Copper (10 cm)	500	Crystalline rock	0.8	27	Bentonite and sand	20.2 b SKr (January 1990)	3.2	34
United States	Spent fuel = 86 800 HLW[i] = 9 500	23 000[j]	92 300	Yes	Stainless steel (1 cm)	300	Tuff	9.1	33	Excavated rock	8.7 b $ (1988)	10.0	38

a) In the case of HLW, the quantity of spent nuclear fuel before reprocessing.
b) Waste volume including canisters.
c) See the glossary.
d) Costs for the selected parts of the waste system in Table 4.1.
e) Approximate numbers.
f) The German estimate assumes a certain amount of reprocessing wastes to be disposed in the same repository for spent fuel, and thus included in Table 6.2 as well.
g) Salt.
h) Granite.
i) Defense high-level waste and West Valley high-level waste.
j) The amount of electricity generation for defense waste is not counted in the corresponding electricity generated.

Table 6.2. **Recent cost estimates for packaging and geological disposal (for disposal of reprocessing waste)**

Country	Spent fuel[a] (tU)	Corresponding electricity generation (TWh)	Volume of waste[b] (m³)	Packaging[c] (for HLW)		Characteristics of the repository					Estimated costs[d]		
				Inclusion of overpacking	Overpack[e] (thickness)	Depth (m)	Host rock	Volume of excavated rock (M m³)	Operating period (year)	Sealing material	In national currency unit (the year of money value)	In billions of US$ of July 1991	Proportion[f] of the underground costs to the total cost estimates (%)
Belgium	3 530	1 160	20 500 HLW: 3 350[g] Alpha: 17 150	No	–	250	Clay	0.24	35-40	Excavated clay[h]	680 M ECU (1990)	0.80	95
France	100 000	25 700	414 000 HLW: 14 000 Alpha: 400 000	No	–	500	[i]	4.8	50	Excavated rock	37 100 M FF (1990)	6.3	50
Germany[j]	35 600 Spent fuel: 25 000 HLW: 10 000 HTR fuel: 565[k]	8 340	96 000 Spent fuel: 26 000 HTR fuel: 18 000 HLW: 4 000 Alpha waste: 48 000	No	–	870	Salt	2.5	50	Excavated rock	7 500 M DM (1988)	4.6	42
Netherlands[l]	2 000	630	139 000 HLW: 4 000 Alpha waste: 3 400 Short-lived waste: 132 000	No	–	600-1 500	Salt	0.57[m]	15	n.a.[n]	860 M f (1985)	0.46	70
Switzerland	4 000	850	24 200 HLW: 4 200 Alpha: 20 000[o]	Yes	Cast steel	1 200	Crystalline rock	0.6	20	Bentonite	1 950 M SF (1990)	1.4	n.a.[n]
United Kingdom	70 000	4 300	3 000 HLW: 2 900 Spent fuel: 100	Yes	Mild steel (6.5 cm)	1 000	Crystalline rock	1.4	20	n.a.[n]	1 000 M £ (1991)	1.7	39

a) In the case of HLW, the quantity of spent nuclear fuel before reprocessing.
b) Waste volume including canisters.
c) "Packaging" and "Overpack"; see the glossary.
d) Costs for the selected parts of the waste system in Table 4.1.
e) High-level waste is normally vitrified in steel canisters (0.5 cm thickness) at the reprocessing site and this cost is not included in the cost estimates in this table.
f) Approximate numbers.
g) 2600 m³ of which is hulls and caps; and some 250 m³ is due to the past operations of the former Eurochemic reprocessing plant.
h) As basic material.
i) No host rock is indicated since different geological media are considered in the estimate.
j) The German estimate assumes a certain amount of spent fuel to be disposed in the same repository for reprocessing waste, and thus is included in Table 6.1 as well.
k) This consists of 54 tonnes of uranium and 511 tonnes of thorium.
l) Reference cost estimates for scenario B, a repository of mine concept situated in a salt dome. Several different cost estimates are described in the country annex of the Netherlands.
m) 0.57 million m³ is a figure for scenario C' but is considered to be close to that for scenario B (scenario B/C': see the Countries Annex).
n) Data not available.
o) Includes alpha-bearing waste from outside the nuclear power programme.

Table 6.3. **Exchange rates for selected OECD countries**

Country	Jan. 1984 NCUs[a] per US$	July 1991 NCUs[a] per US$	Change in value of NCU against US$
Belgium	57.75	36.82	+57%
Canada	1.25	1.15	+9%
Finland	5.94	4.29	+38%
France	8.61	6.07	+42%
Germany	2.81	1.79	+57%
Netherlands	3.17	2.01	+58%
Spain	158.73	111.99	+42%
Sweden	8.18	6.47	+26%
Switzerland	2.24	1.55	+45%
United Kingdom	0.71	0.61	+16%
United States	1.00	1.00	–

a) NCU stands for national currency unit.

Table 6.3 shows the currency exchange rates used in this report using the US dollar as the base currency. It also illustrates one of the uncertainties introduced into these comparisons: the value of the other national currencies have all increased against the US dollar between January 1984 and July 1991. The increases range from 9 per cent for Canada to 58 per cent for Netherlands. Therefore, the results of these comparisons in 1984 would be quite different from 1991, owing solely to the change in currency exchange rates.

The final sub-column provides the proportion of the underground costs to the total costs estimated. It should be noted that the distinction between the underground and surface costs could be made in many different ways. The proportions are approximate and can be only used for the tables in this chapter.

Although comparisons are possible within each table (Table 6.1 or 6.2), the reader should recognise that the stage of development of the disposal systems varies among the countries. The summary tables illustrate that various factors underlying the cost estimates are significantly different from each other and the resultant cost figures appear to show a significant variation. The factors affecting disposal/packaging cost estimates will be further discussed in Chapters 7 and 8.

6.2. Comparison of normalized costs

The cost estimates provided by participating countries vary over a significant range because of national nuclear strategies, scale of nuclear programmes, reactor designs and other factors. In order to compare the costs, the costs must be normalized to a specific cost basis in a way that will remove some of this variability. In the following paragraphs, different ways of normalizing the costs are discussed and the normalized costs are compared.

The cost estimates are normalized in several ways in Table 6.4 for the direct disposal of spent fuel and in Table 6.5 for disposal of reprocessing wastes. All normalizations in these tables are intended to reduce the effect of the differences in the magnitude of the disposal programmes.

In Tables 6.4 and 6.5, the left-hand column provides the cost estimates without normalization. The other four columns marked with a capital letter provide normalized figures described below:

Column [A]: the total costs (in Tables 6.1 and 6.2) proportioned to the amount of electricity generated (M$/TWh). The radioactivity and decay heat produced by the spent fuel (or high-level waste resulting from reprocessing the fuel) correspond directly to the heat energy produced in its service. This corresponds quite closely with the electrical energy produced, as the majority of nuclear power plants have a thermal efficiency of around 30 per cent. A few outlying systems have thermal efficiencies from 20 per cent (earliest Magnox) to 40 per cent (best AGRs). This normalization is introduced in order to take into account the differences in fuel burnup, which may be seen to affect directly the heat-load related-costs at the repository.

Column [B]: the total costs (in Tables 6.1 and 6.2) proportioned to the amount of uranium in the waste to be disposed of (k$/tU) (in the case of disposal of reprocessing waste, the amount of uranium in the spent fuel before reprocessing is used). This normalization method has sometimes been used within the nuclear industry and by the press and other publications.

Table 6.4. **Normalized cost estimates for encapsulation and disposal**
(for disposal of spent fuel)
Costs are presented in July 1991 US dollar

Country	Total cost	**Cost per unit electricity generation** **[A]**	Cost per unit weight[a] of wastes [B]	Cost per unit volume of wastes[b] [C]	Underground cost[c] per excavated rock volume [D]
	B$	**M$/TWh**	k$/tU	$\mathrm{k\$/m^3}$	$\mathrm{\$/m^3}$
Canada	8.7	**0.80**	46	90	560
Finland	0.76	**1.8**	410	290	1 200
Germany[d]	4.6	**0.55**	130	96	1 100
Spain[e]	2.4	**1.3**	360	60	500
Spain[f]	2.0	**1.1**	300	180	1 400
Sweden	3.2	**1.6**	410	250	1 400
United States	10.0	**0.43**	100	110	420

a) In the case where high-level waste will be disposed of with spent fuel, the weight of uranium in the spent fuel before reprocessing.
b) The volume of spent fuel (and high-level waste) including containers.
c) Approximate numbers.
d) In the German estimate, a certain amount of reprocessing waste is assumed to be disposed of in the same repository as for spent fuel, and thus the German estimate is included in Table 6.5 as well.
e) The cost estimate for salt formation.
f) The cost estimate for granite formation.

Column [C]: the total costs (in Tables 6.1 and 6.2) proportioned to the waste volume including disposal containers ($\mathrm{k\$/m^3}$). This normalization is introduced in order to take into account, in addition to the differences mentioned above, the differences in waste packaging. For reprocessing waste, only the volume of high-level waste is considered in the normalization, as the cost for the disposing of this waste is generally much higher than the assumed disposal costs of alpha-bearing waste.

Column [D]: the costs for underground activities proportioned to the volume of rock excavated from underground ($\mathrm{\$/m^3}$). The rock volume directly represents the physical volume of the repository. This normalization may partially take into account differences in cooling periods, repository designs, etc.

Table 6.5. **Normalized cost estimates for encapsulation and disposal**
(for disposal of reprocessing waste)
Costs are presented in July 1991 US dollar

Country	Total cost	**Cost per unit electricity generation** **[A]**	Cost per unit weight[a] of wastes [B]	Cost per unit volume of wastes[b] [C]	Underground cost[c] per excavated rock volume [D]
	B$	**M$/TWh**	k$/tU	$\mathrm{k\$/m^3}$	$\mathrm{\$/m^3}$
Belgium	0.8	**0.69**	230	240	3 200
France	6.3	**0.25**	60	450	660
Germany[d]	4.6	**0.55**	130	96	1 100
Netherlands	0.46	**0.73**	230	110	560
Switzerland	1.4	**1.65**	350	330	–
United Kingdom	1.7	**0.40**	25	560	470

a) In the case of high-level waste, the weight of uranium in the spent fuel before reprocessing.
b) The volume of high-level waste (and spent fuel) including containers.
c) Approximate numbers.
d) In the German estimate, a certain amount of spent fuel is assumed to be disposed of in the same repository as for reprocessing wastes and thus the German estimate is included in Table 6.4 as well.

The cost estimates for the direct disposal strategy (Table 6.4)

The cost estimates in Table 6.4 have a fairly similar basis. Most of them include both the costs for disposal and packaging, and assume that all or almost all of the waste to be disposed of is spent fuel. In the case of the German estimate, a substantial amount of high-level waste, as well as spent fuel, is assumed to be disposed of. However, it goes without saying that various differences underlying the cost estimates remain, such as repository design, canister design, geological medium, etc.

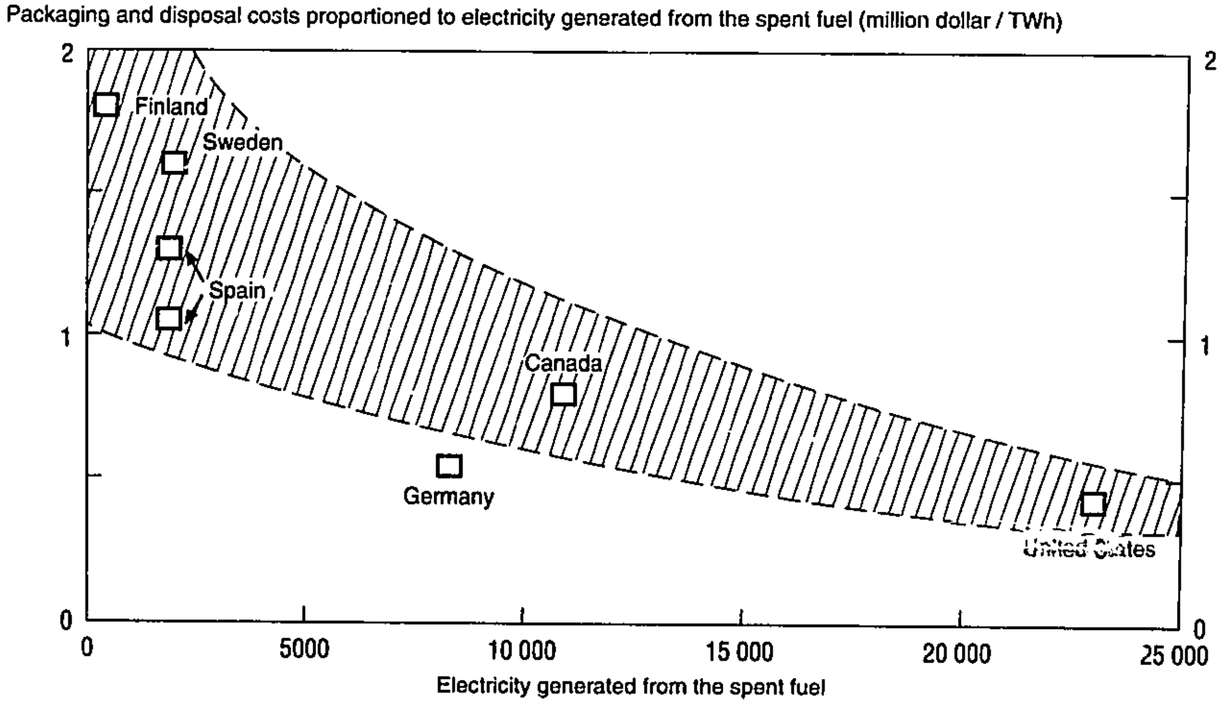
The total costs reported for the packaging and final disposal of spent fuel vary between $ 0.76 billion for Finland and $ 10.0 billion for the US. The most important factor in this large variation is, of course, the amount of fuel to be disposed of.

In column [A], the costs are normalized to the costs per TWh of electricity produced in the fuel to be disposed of. This normalization takes into account the fact that the waste density in the disposal facility is dependent on the heat generation rate, which is in turn dependent on the total energy generated by the fuel. The costs normalized in this way fall within a factor of 4.1.

The low figures of Canadian and US estimate in Column [A] may suggest the economy of scale in the packaging/disposal cost estimates, *i.e.*, the larger the disposal programme, the cheaper the unit disposal cost. The nuclear programmes assumed in the US and Canadian estimates are considerably larger than those of others. This is shown in Figure 6.1, in which the normalized costs in Column [A] of Table 6.4 are plotted against the amounts of electricity generated from the spent fuel. The low figure of German estimate may be explained by its assumption that a certain amount of reprocessing waste will be disposed of in the same repository as the spent fuel. It should be recognised that the economy of scale can be seen in all the columns.

In column [B], the total cost has been normalized to the cost per tonne of uranium to be disposed of as sometimes used in the press. After this normalization, the costs for Finland, Spain and Sweden are fairly similar, while the costs for Canada and the US are substantially lower. The low Canadian figure could partially be explained by the low burnup of the spent fuel in CANDU reactors. While a typical burnup is 35 000-40 000 MWd/tU for light water reactor fuel, the burnup of the CANDU fuel is around 8 000 MWd/tU. The resulting lower heat generation in the Canadian spent fuel leads to more compact disposal and lower costs

Figure 6.1 **Normalized costs (M$ / TWh) plotted against electricity generated (TWh)**
(For direct disposal of spent fuel)



per tonne of uranium. The lower US cost is probably due to a scale effect and the high thermal loading assumed in the US repository design.

In column [C], the costs are normalized to the costs per m^3 of waste disposed of (including packages). The same tendency can be found here as in the other columns. The variation is a factor of 4.7 and may be partially due to differences in thermal limitations and packing densities in the repository.

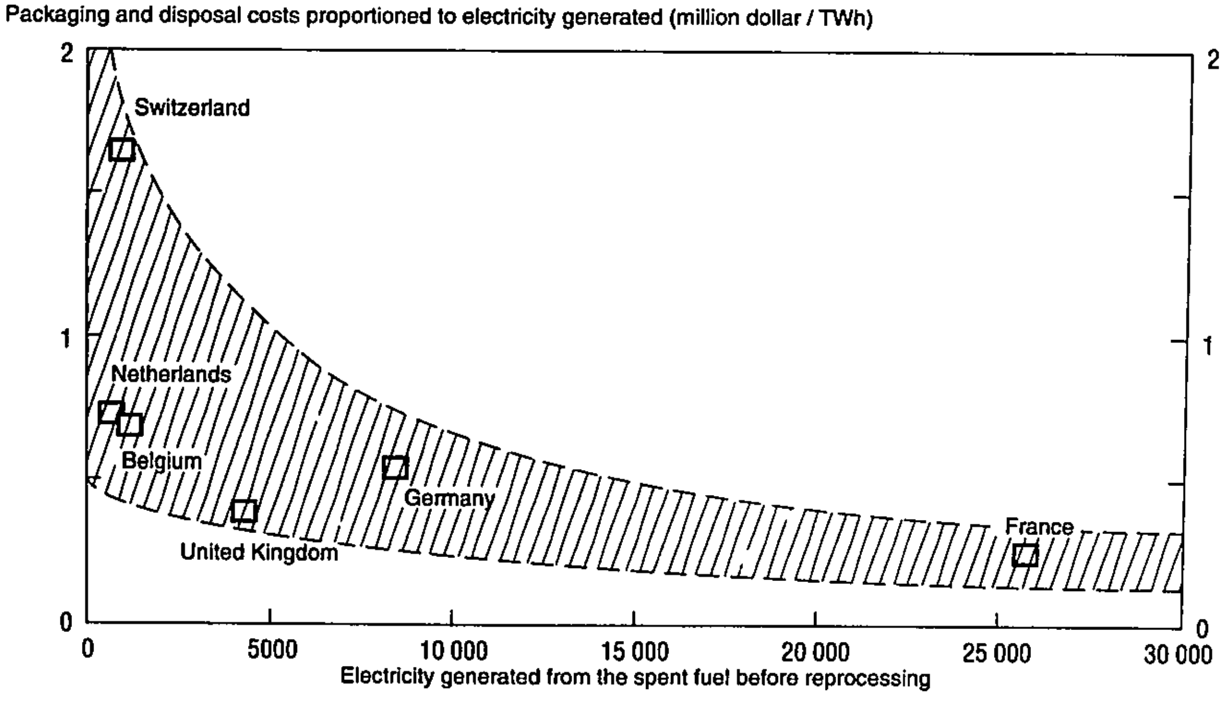
In column [D], only the cost for underground work (excavation, disposal, backfilling and sealing) is normalized to the total volume of rock excavated. In the case of crystalline rock, the results show the effect of scale, but also indicate that the basic costs are different in Europe and in North America. In the US case also, the low cost of backfilling and sealing has an influence, as crushed tuff will be used. The results also indicate that the normalized cost is dependent on the geological medium of the repository.

The cost estimates for the reprocessing strategy (Table 6.5)

As the assumptions made for disposal cost estimates for reprocessing wastes have larger divergencies than those for spent fuel disposal, the comparison has less relevance. The Belgian, French, and Swiss estimates are given for disposal of high-level and alpha-bearing waste from reprocessing, while the German estimate also assumes a certain amount of spent fuel to be disposed of in the same facility. The British estimate assumes that only high-level waste and some spent fuel will be disposed of in the repository, while the Dutch estimate assumes that all radioactive waste produced in the country (not only high-level waste and alpha-bearing waste from reprocessing but also low and intermediate level waste from reactor operation and hospitals, etc.) will be disposed of. Also, the use of an extra overpack differs between the estimates. The Swiss and UK estimates include the cost of packaging in an overpack, while in the other estimates no need is assumed for packaging other than for canisters produced at the vitrification facility.

The total costs reported for the systems vary between $ 0.46 billion in the case of the Netherlands and $ 6.3 billion for France. In columns [A] to [D] of Table 6.5, the same type of normalizations are done as for the disposal of spent fuel. For the reasons given above, however, the intercomparison is more difficult here and one expects to find larger differences. The same tendency can, however, be found as for the spent fuel, *e.g.*, the effect

Figure 6.2 **Normalized costs (M$ / TWh) plotted against electricity generated (TWh)** (For disposal of reprocessing waste)



of scale (for France), the effect of lower fuel burnup (for the UK) and the effect of an overpack (for Switzerland and the UK).

The smallest variation is found when the costs are normalized by division with the volume of high-level waste (column [C]). For this normalization, the costs fall within a factor of 5.8. The low German estimate may be explained by a large volume of spent fuel including canisters and overpacks (spent fuel: 43 500 m^3, high-level waste: 4 200 m^3).

As was shown in the estimates for spent fuel disposal, the estimates for reprocessing scenarios in Table 6.5 also illustrate the economy of scale. However, because of the variation of assumptions made in the estimates, the effect of the economy of scale is not so clear as in the case of estimates for direct disposal scenarios. This is shown in Figure 6.2, in which the normalized costs in column [A] of Table 6.5 are plotted against the amounts of electricity generated from the spent fuel. The high figure of the Swiss estimate may be explained by exceptionally voluminous overpacks involved in their concepts and the greater depth of disposal. The low figure of the UK estimate may be explained by the assumption that only high-level waste and small amounts of spent fuel will be disposed of to the repository.

In column [D], the cost for underground work is normalized to the volume of rock excavated. The figures found are fairly similar to the corresponding figures for spent fuel disposal, as could be expected.

General observation

The cost comparisons made in this chapter have been restricted to packaging and disposal in order to remove the largely country-specific costs of R&D and siting activities. To reduce further the influence of size-dependent factors, we have normalized the costs on several bases. It is shown that the wide variation of the original cost estimates can be explained by factors such as the magnitude of the nuclear programme, fuel burnup and the amounts of non-high-level waste to be disposed of in the same repository. When the cost estimates are proportioned to the amount of corresponding electricity generation, the normalized cost estimates, with some exceptions, fall in a relatively narrow range, as shown in Tables 6.4 and 6.5. This seems to indicate that the disposal cost estimates of spent fuel and reprocessing waste are reasonably well understood. The usual fuel cycle normalization of "per tonne of uranium" may introduce major distortions if wastes from different reactor types are assumed.

However, as can be seen, there still remain considerable differences among the cost estimates for each disposal strategy (Tables 6.4 and 6.5). These differences are partially caused by the fact that since packaging and geological disposal are future activities, and plans are still preliminary, the cost estimates are subject to uncertainties to some extent.

The differences are also caused by factors that cannot be readily normalized with the methods adopted in this chapter. They include differences in geological medium, repository design, type of disposal canister, regulations, etc. The Countries Annex for the Netherlands provides the variation in cost estimates caused by differences in geological medium and repository designs. This is also the case for the two Spanish estimates. The Countries Annex for the UK provides a cost algorithm that can be evaluated for a range of factors, such as number of waste canisters, total heat output from the waste and repository operating lifetime. These factors are discussed further in Chapters 7 and 8.

It should be noted that the numeric values described in the tables should not be taken too literally, since the number of the estimates submitted to this study is limited and the monetary conversion is affected by fluctuating exchange rates.

6.3. Relative importance of the components of the cost estimates

In the Countries Annex (Annex 1), the cost estimates are broken down into various levels of detail. From this detailed breakdown, the following observations can be recorded.

a) The final columns of Tables 6.1 and 6.2 provide the proportion of the underground costs to the total costs estimated. The data show that the cost for underground work is not necessarily a dominant element in the overall packaging/disposal cost estimates. The percentage of the total costs that relate to underground facilities construction and operations, in the case of the direct disposal approach, falls in a narrow range (29 per cent to 46 per cent) while, in the case of the reprocessing approach, it varies significantly with strategy, capacity and organisation, from 33 per cent (UK) to 95 per cent (Belgium).

The percentage is usually smaller in direct disposal scenarios than in reprocessing scenarios, because most of the cost estimates for disposal of reprocessing waste do not assume additional packaging at the repository site. Among the estimates for the reprocessing approach, the low figure of the UK may be explained by the fact that all the operating costs are in the surface costs centre. The high Belgian estimate is explained by the design and concept of its repository.

b) The percentage of the total cost of decommissioning and sealing operations varies from 4 per cent [Belgium, France and Spain (salt)] to 18 per cent [Spain (granite)], depending largely on system capacity and whether sealing is included in the operation costs.

c) The relationship between construction costs for the packaging plant and repository, the costs for operation, and the costs for decommissioning and sealing is very dependent on the way in which the repository costs are handled. In most concepts, there is continued excavation and servicing of new disposal areas during the period of repository operation. In some estimates, this work is considered as an operating cost, while in others it is a construction cost.

6.4. Summary of research and development and site screening and evaluation costs

The Countries Annex include data from the various countries on the estimated cost of the R&D still required to implement waste disposal, and on the cost of site screening and evaluation (generally the technical costs only). To give the reader a complete picture, the cost estimates in the Countries Annex are summarised in Table 6.6 in respective national currency units for the year of the estimate. The table shows that these costs are essential and may add 10 to 80 per cent to the total estimated costs for design, construction, operation, decommissioning and closure of the packaging and disposal facilities. It should be recognised that direct comparison of the estimated costs between the countries is meaningless because the definition and coverage of these costs differ significantly from country to country.

Table 6.6. **Summary of estimated costs for research and development and siting**[a]

Included in the cost estimates submitted to the study

Country	Currency unit (the year of money value)		Research and development and siting costs	Proportion to total estimated costs in Tables 6.1 & 6.2
Belgium	M ECU	(1990)	100	22 %
Canada	M CAN$	(1990)	805[b]	9 %
Finland	M FIM	(Dec. 1990)	530	16 %
France	M FF	(1990)	3 000	8 %
Germany	M DM	(1988)	1 500[b]	20 %
Spain	Billion Ptas	(1991)	110	42-50 %[c]
Sweden	M SEK	(Jan. 1990)	4 000	20 %
Switzerland	M SF	(1990)	900	46 %
United Kingdom	M £	(1991)	194	19 %
United States	M US$	(1988)	6 746	77 %

a) The data for the Netherlands are not available.
b) Cost estimation for R&D is not included.
c) Salt and granite.

6.5. Impact of the uncertainties in the cost estimates

The previous NEA studies concluded that the cost for packaging and disposal of spent fuel and reprocessing waste accounts for only a few per cent of the total fuel cycle costs in levelised cost calculations [1], and the total fuel cycle cost of LWRs is only around 20 to 40 per cent of the total cost of generating nuclear electricity [2]. Therefore, quite large uncertainties in the disposal cost estimates will have only a small impact on the cost of nuclear electricity generation.

In some countries, disposal cost estimates have been performed to determine the amount of funds needed for future disposal, and hence the fee to be paid by electricity consumers. In these cases, great care has been taken to implement contingencies in order to avoid underestimating the future costs. Therefore, the present cost estimates can be used as a basis for defining the amounts of the liabilities.

Chapter 7

TECHNICAL FACTORS OF IMPORTANCE FOR THE COSTS

7.1. Introduction

As was briefly discussed in the preceding chapters, a number of factors, both technical and non-technical, will affect the results of the cost calculations. In order to understand the differences between the results reported in different countries, it is important to have a good understanding of these factors. It is also important for the person who makes the cost calculations to understand the importance of the different factors and how changes in the factors might affect the results.

This chapter reviews the technical factors that are of importance and must be defined by those calculating costs. The next chapter presents other non-technical factors, such as social/political factors. Unless a different indication is given, the impacts of factors are described for the costs in constant money value. Safety issues are not discussed in this report, although they constitute the most important criterion for the definition of the disposal strategy and the repository design. The issue of cost optimisation is secondary to safety.

Three categories of technical factors can be classified according to their importance in cost estimates:

- major factors important in all projects;
- special/specific factors important in some projects;
- minor factors with a relatively lower cost influence.

Table 7.1 shows these different technical factors. They have been grouped into six categories:

- Project definition: factors that are dependent on national circumstances, such as nuclear programme, recycling strategy, and scope of the cost estimates.
- Disposal strategy: factors connected to the time schedule.
- Site services: infrastructure and service facilities.
- Packaging facility: factors connected to the choice of container and packaging.
- Reception facility: activities carried out on surface and related to the reception of waste packages delivered to the disposal site.
- Repository: factors connected to the siting, design, construction, operation and closure of the repository.

In addition to these points, the cost of labour and differences in productivity between different countries should also be considered.

7.2. Project definition

7.2.1. *Nuclear programme*

The reference nuclear programme is the source for the spent fuel or reprocessing waste to be included in the cost calculations. It is thus important to define the number of reactors assumed as the basis of the disposal programme, the type and capacity of the different reactors, and the time of operation assumed for each reactor. This defines the amount and type of fuel to be disposed of.

As the size of the disposal facilities is important for the total costs, the amount of fuel or reprocessing waste considered in the cost estimate is important. The total cost for disposal normally increases with an increase in the amount of material planned for disposal. Because many costs are fixed and not volume-dependent, the specific costs of disposal decrease with increasing amount of waste. In the examples given in this report, the amount of fuel ranges from 190 000 tU in Canada to 1 800 tU in Finland, with corresponding specific costs of

Table 7.1. **Technical factors affecting the cost calculations for packaging and final disposal of spent fuel or reprocessing wastes**

	Major factors important for all projects	Factors important for some projects	Factors generally of low importance for cost estimates
Project definition	Nuclear programme Fuel management strategy and waste type Scope of cost estimate		
Disposal strategy	Barrier system	Cooling period Operating period Retrievability and monitoring	Timing of conditioning
Site services		Infrastructure	Surface facilities
Packaging facility		Packaging method Container type and material	Design of facility Technology status
Reception facility		Design of facility	
Repository	Geology Scale of repository	Temperature restrictions Sealing systems	Residual value of rock Depth of repository Design of repository Construction and operation strategy Technology status

$ 0.05 to $ 0.4 M/tU and, for reprocessing countries, from 100 000 tU (amount of uranium in the spent fuel before reprocessing) in France to 2 000 tU in Netherlands, with specific costs of $ 0.07 and $ 0.2 M/tU.

The type of reactor is also important, as the spent fuel characteristics, such as design, activity content and heat release, will vary among reactors. For example, the low-burnup fuel used in CANDU reactors has a much lower heat release per tonne of uranium than LWR fuel, and can thus be disposed of in a more compact manner, giving a lower specific disposal cost per tonne of uranium, although the specific costs per kWh might be similar.

Figures 6.1 and 6.2 show the disposal cost per unit of electricity generated versus total nuclear electricity production for direct disposal and reprocessing in the different countries. A scale effect can be noted.

7.2.2. Spent fuel management strategy, type of waste and waste characteristics

In this report only the disposal of spent fuel or reprocessing wastes (high-level vitrified waste and alpha-bearing waste) is discussed. The characteristics of these waste types are significantly different, as explained in Chapter 2. These differences could have a significant effect on the disposal costs.

The design of a repository for spent fuel and one for reprocessing waste could be fairly similar if the distribution of the spent fuel or waste is controlled by the heat output. For this case, the volume of rock required for heat dispersion will be similar. The thermal output of waste is a function of cooling time prior to emplacement in the repository. However, the smaller size and number of the vitrified waste disposal canisters might permit a smaller tunnel system and fewer disposal areas in the reprocessing waste repository.

Alpha-bearing waste from reprocessing and high-level waste can be disposed of in different areas of the same repository, or in separate repositories. The design of a separate disposal facility for alpha-bearing wastes will probably be very different, as they normally generate a very small amount of heat, and can thus be packed closer together.

7.2.3. Scope of the cost estimate

The spent fuel management system consists of a number of different activities, including interim storage, transport, reprocessing, waste treatment, packaging and disposal. Each of these activities is also composed of sub-activities that are necessary in some systems and not in others. It is thus important to define clearly what is included in the presented cost estimate and what is not. In this report, the cost estimates have been restricted to packaging and final disposal. Other costs have been discussed but not included. It should, however, be recognised that, *e.g.*, the time of operation of the other facilities, such as the interim storage facility, will have an impact on the costs for packaging and final disposal.

7.3. Disposal strategy

7.3.1. Barrier system

The repository is generally designed as a multi-barrier system. The waste form; the container and overpack if used; the sealing system; and the host geological formation constitute barriers against radioactive release. As part of the whole system, the role of each barrier may vary from one project to another, depending on its expected long-term behaviour or on the safety philosophy. Thus, in some cases, an extra overpack is used, while in others it is not needed. The costs of overpacking could be a substantial fraction of the disposal costs.

7.3.2. Cooling period

If thermal loading is the limiting factor for the design of the repository, one of the most important factors affecting the cost of final disposal of the spent fuel or reprocessing waste is the cooling period considered between removal of the spent fuel from the reactor and actual disposal of the fuel or waste. During the first years after removal from the reactor, the heat emission from the fuel decays fairly rapidly. The rate of decay, however, decreases when the short-lived radionuclides have decayed and the heat comes from more long-lived radionuclides (see Figure 2.2).

Between one and 40 years after removal from the reactor, the heat emission from a fuel element or high-level vitrified waste decays by a factor of ten. Between 40 and 100 years the decay is only a factor of 2 for spent fuel while it is a factor of 4 for high-level vitrified waste. The difference in heat decay is due largely to the removal of plutonium from the waste during reprocessing of the spent fuel.

As the heat emission decays, more waste can be stored in the same container or borehole and/or the containers can be placed closer together, depending on the relative thermal limitations and criticality aspects of the waste package, the host rock or other aspects of the design. All these factors will lead to lower costs for the disposal with longer cooling periods. At the same time the costs for interim storage will increase. A US study shows that a delay of the repository by 50 years decreases the repository costs (in constant money value) by 4 per cent but this would be more than offset by an increase in the interim storage costs of 53 per cent and that the total system cost would increase by 15 per cent. Studies done in Sweden with their technical criteria show that these factors counterbalance in constant money, but that if the present-value method is employed for the calculation there will always be a decrease in the present value of the costs with longer cooling times. The Swedish studies show, for example, that a shortening of the storage period from 40 to 25 years would increase the present value of the cost by 20 per cent (at 2.5 per cent real interest rate) for the same temperature reached in the repository. Other thermal criteria could lead to different results. Non-technical considerations also have a significant influence on the cooling period. UK studies support the economic benefit of storage to achieve further cooling.

For the alpha-bearing waste from reprocessing, an increase in the cooling time has only a minor impact as long as the repository design is selected properly. The interim storage period for this waste may be governed by other factors, such as possible co-location of the alpha-bearing waste disposal with the high-level waste disposal.

7.3.3. Operating period

The annual costs of operating a packaging facility and a repository are composed, to a large extent, of fixed components that are not very sensitive to the annual capacity of the plant. The length of the operating period may thus have an important impact on the total costs for disposal. However, consumable supplies for operation, such as disposal containers, are directly related to plant capacity, not to the operating period.

A Belgian study shows that the lengthening or shortening by 10 years of the operating period from the reference case of 30 years may respectively increase the total costs by 13 per cent or decrease them by 19 per cent at the maximum.

At the same time, a change in the length of the operating period will also affect the average cooling time of the waste to be disposed of, which will also affect the costs as described above.

In the presented cost calculations for disposal systems, two different strategies can be observed. Either the waste is disposed of after a certain cooling period, which means that the disposal is carried out at the same rate as the fuel is removed from the reactor, or a fixed disposal capacity is assumed, which means that the cooling time will vary.

In the small systems, the operating periods may be longer than the full capacity of the facilities would require. In the Finnish estimate, the operating period for an encapsulation facility and final repository is assumed to be 20 years, in order to allow the spent fuel to be cooled sufficiently. With the full capacity of the encapsulation station, the operating period would be only 13 years. The lengthening of the operation by seven years would increase the total operation costs of the encapsulation facility and repository by 20 per cent (mainly in staff salaries).

7.3.4. Retrievability and monitoring

In some countries there is a legal requirement that the waste remain retrievable for a certain period of time after disposal. This could mean that the repository will have to be kept open during this period, which will have an impact on the operating costs.

Alternatively, special design modifications may need to be introduced to enable retrieval after closure, which also will have a cost impact.

In the US estimate, an additional 17-year operating phase after final waste emplacement to maintain retrievability increases the total cost by 4 per cent.

In some countries there is also a legal requirement for extended monitoring after emplacement of the waste. This factor can be a potential cost in design and operation, especially if a long monitoring period is assumed.

7.3.5. Timing of conditioning

Normally, it is assumed that the spent fuel or high-level vitrified waste (if needed) is packaged in connection with the actual disposal of the material. As an alternative, the conditioning could be performed earlier. This factor is not deemed to have any great impact on the cost of packaging and disposal, as long as packaging costs are consistently included in or excluded from the total costs.

7.4. Site services

7.4.1. Infrastructure

The packaging and repository facilities are dependent on an existing infrastructure, *e.g.*, electricity and water supply, roads and railways, community housing, schools, etc. The costs of the infrastructure will be strongly dependent on the location of the facilities and the distance to the closest cities or villages.

As the waste will be transported by rail, road or water, the cost of railways, roads and harbour facilities could be substantial. In some cases, it might be necessary to build a new railway line and/or roads for tens or even hundreds of kilometres – as well as possibly constructing docking and handling facilities – at a large cost. Some cost estimates take into account the cost of these facilities: for example, a 50-km-long rail line and a harbour, corresponding to about 10 per cent of the total construction costs, are included in the Swedish estimate. In the US estimate for the Yucca Mountain candidate site, the total cost for the infrastructure, which includes construction of roads and construction of a 160-km rail line as well as other infrastructure facilities, is $ 351 million, which is 4 per cent of total repository costs.

If a virgin site is chosen, there might be a need to build a new village with houses, shops, community facilities, and any other necessary infrastructure.

Alternatively, the packaging facility and the repository could be co-located with the interim storage facility. In this case, the need for a new infrastructure will be diminished as some of the necessary facilities will already exist and expansion alone may be sufficient. As an example, there will be no need for additional transport equipment to move the waste on the surface.

When evaluating different cost calculations, it is important to know which parts of the infrastructure are included in each.

7.4.2. *Surface facilities*

In addition to the packaging or reception plant and the hoisting house, a number of other surface facilities will be needed at the final disposal facility. Examples are stores, offices, a records archive facility, fire protection, mechanical workshops, vehicle service, concrete station and facilities for crushing rock and handling and preparating the sealing materials. The extent to which these are included will also affect the costs. In the US study, the cost for surface facilities (excluding packaging and hoisting facilities but including buildings for testing the performance of waste packages, the decontamination building and waste treatment building) is estimated at about 17 per cent of the total repository cost.

7.5. Packaging facility

7.5.1. *Packaging method*

The process used to package the waste before disposal can have an important impact on the costs of disposal. At one extreme, no extra packaging is needed and thus no packaging facility is required. This is probably the case for alpha-bearing waste from reprocessing and could also be the case for high-level vitrified waste if the canister (in which the waste is vitrified at reprocessing plant) or the waste form is considered to have properties that are acceptable as part of a multi-barrier system for disposal. A packaging plant might also be unnecessary if packaging in disposal containers takes place at the reactor, the reprocessing plant, etc.

At the other extreme, a quite sophisticated conditioning process could be assumed. One example of this is the copper canister proposed as an alternative in Sweden for the encapsulation of spent fuel, where a hot isostatic pressing process is utilised to sinter the copper powder filling the voids around the fuel pins with solid copper. This process is done at high temperature and pressure.

Other packaging processes involve putting the fuel or waste in a strong canister, possibly backfilling it with a material such as sand or lead, and then welding a lid onto the canister. In some concepts, a double lid system is foreseen.

The spent fuel or waste may be preconditioned before packaging. In particular, this is applicable to the spent fuel, where the fuel assemblies in some systems are dismantled and the fuel pins are packed closer together before packaging. In some cases also, the fuel pins are assumed to be cut into shorter segments so that they can be packaged in a canister with dimensions and mechanical-handling features similar to those of a vitrified waste canister.

These different processes will all have an impact on the layout of the packaging facility and on the systems required for worker, environmental and public safety, and will affect the costs. In a German study, the investment costs for a fuel-packaging plant increase by 20 per cent if a rod-cutting process is used.

7.5.2. *Container type and material*

Many different containers have been proposed for disposal of spent fuel or high-level vitrified waste. Among the concepts, two different categories can be distinguished according to different engineered barrier concepts. One category refers to containers with an expected service life of a few hundred to a thousand years. Materials discussed are carbon or stainless steel and titanium. The other category refers to containers with an expected service life of hundreds of thousands of years. The materials considered for this category include copper and, at a lesser state of development, ceramics.

The design of the container will have a significant effect on the design and costs of the packaging facilities. Thick-walled container designs that will sustain the pressures imposed in a disposal environment and provide the necessary waste isolation will require more material and fabrication work, but will not require filler materials (*e.g.*, particulate or solid matrix). A thin-walled design usually requires complete filling of internal voids, as it is not self-supporting. This will add extra steps to complete the waste packaging, may require high-temperature processes and different materials, and will increase costs.

The choice of container affects the processes utilised in the packaging facility and the layout of the facility. Also the size and need for shielding of the containers affect the layout of the repository and its handling equipment.

The material costs for different containers can also vary substantially, *e.g.*, between a carbon steel canister and a copper canister. Nevertheless, as much of the container cost arises in manufacturing and especially in quality control, this factor may not be so important for the total cost. In the Swedish study, the cost for packaging diminishes by about 15 per cent if a steel rather than a copper canister is used.

7.5.3. Design of facility

Many different designs of packaging facilities have been presented. The differences are mainly due to differences in the processes used for packaging, as previously discussed. There may also be a difference in the planned function of the facility. In some cases, for example, a large buffer storage area is provided for the incoming fuel (*e.g.*, in pools), while in others the transport casks are used as buffer storage. Another example of difference in planned function is that, in addition to the packaging of the spent fuel, a treatment facility for core components and fuel channels could also be included.

The philosophy adopted for system redundancy is also important. If, for instance, parallel conditioning lines are installed to avoid a stoppage in the flow of material, the costs will be greater with no real change in the capacity of the plant, than for a situation where a stoppage is accepted and a single conditioning line is utilised.

The design of the packaging facility for spent fuel must, of course, be such that it guarantees proper radiation protection, a trustworthy safeguards regime and a good quality control system. These factors are important for the layout of the facility but are not expected to have a large impact on the cost differences.

7.5.4. Status of technology

The technology assumed in the cost estimates for packaging is sometimes based on existing and proven methods, and at other times on adaptation and extrapolation of existing methods. In the latter case, the cost for necessary development work and the estimated costs of installing and operating the developed process will have a larger uncertainty and this uncertainty must be considered in the cost calculations.

7.6. Reception plant

In the case of reprocessing waste that will be disposed of without an additional overpack, a reception facility will still be needed. Reception of waste at the disposal site includes unloading of the transportation cask, control and preparation of the waste package, buffer storage and loading of the handling cask before underground transfer.

The design of the plant depends on the waste delivery rate, established by defining the number of cask-unloading lines or the capacity of the buffer storage. As for the packaging plant, the philosophy for system redundancy is important. It must be reliable in order to minimise stops in the flow of waste delivered to the repository. The design of the plant must also meet all safety requirements related to irradiation and environmental protection.

7.7. Repository

7.7.1. Geology

As geological conditions vary among countries, the different geological media considered for the repository vary as well, *e.g.*, salt in Germany, clay in Belgium, tuff in the United States and crystalline rock in Canada. It has been shown that a safe final repository could be built in many different types of geological media [6, 7].

The techniques for construction and operation of a repository will vary between the different media. For example, in crystalline rock, the tunnels and rooms may be kept open for a long period without special support, while in clay support structures must be constructed during excavation. Also, the size of the openings could be much larger in crystalline rock. These factors may affect the size of the canisters and, certainly, the costs of the underground work.

Another important difference is the fact that a salt repository is almost completely dry, while some water will have to be collected and removed in a crystalline repository.

A US study concluded that different geologic settings could vary the repository costs by as much as 100 per cent. The Spanish study estimates the total packaging/disposal costs for salt rock to be about 20 per cent higher than the cost for granite rock. However, these cost differences may also be partially caused by other factors, such as container type and repository depth.

7.7.2. Scale of the repository

The disposal cost for a given volume of waste depends on the total amount of waste to be disposed of in a repository. However, the cost is not proportional to the waste amount. Indeed, a substantial investment will be relatively constant, irrespective of how much waste will be disposed of. This investment relates, for example, to a number of shafts or ramps equipped with the necessary lifting, ventilation, services supply and communication equipment. The volume or mass of waste will thus have an important impact on the specific disposal costs.

The marginal cost as a percentage of the total costs varies from 20 to 60 per cent for an incremental increase in the repository. In a German cost study, about 80 per cent of the total costs are fixed and in the Swedish case about 50 per cent are fixed. In a US study, it is shown that a 38 per cent increase in the quantity of waste results in a 25 per cent increase in the repository cost; however, if a second repository is needed, a 38 per cent increase in waste quantity would result in 94 per cent increase in the total repository cost. In a Finnish study, it is shown that a 192 per cent increase in the quantity of waste (630-1840 tU) results in a 95 per cent increase in the disposal cost (design, construction, operation, decommissioning and sealing of the repository).

7.7.3. Temperature restrictions

One of the limiting factors for the design of a repository is the allowed temperature increase in the near field around the container and in the rock. The temperature rise should be controlled to limit adverse thermal effects in the repository and its surroundings. The allowable increase is a function of the thermal limits of the waste package, the sealing systems and, most importantly, the geological medium. These limits depend on the materials selected and the respective importance of the different barriers in the disposal system.

The temperature increase is directly related to waste heat output, which is a function of the age, composition and amount of waste in each container, and the spacing between the containers. Therefore, specific selection of these various design elements has a large impact on the costs when temperature is a limiting criterion. A Swedish study shows that decreasing the temperature limit by 10°C would increase the cost by 10 per cent for their specific concept.

7.7.4. Sealing systems

The sealing material used around the waste containers and in the tunnels constitutes an important part of the repository costs, both by their direct cost and by the temperatures limits of the sealing material. Different types and qualities of sealing material have been studied. In salt repositories, crushed salt is normally used. In clay repositories, excavated clay is used. In crystalline rock repositories, multimedia seals comprising swelling clay or other material (*e.g.*, bentonite mixed with sand, crushed rock, grouts and concretes, etc.) are being considered. In the Canadian concept, in which swelling-clay-based seals are considered, the percentage of the sealing material costs to the total cost is estimated at about 19 per cent The material costs are normally lower if the excavated material can be reused, if the amount of preparation for the sealing materials is minimised, and if the amount of swelling clay can be kept low.

7.7.5. Residual value of rock

The excavated rock is often considered in the cost calculations to be a waste product that introduces a cost for its management. In many areas, however, excavated and crushed rock material is regarded as an asset and can generate revenue for the repository. In cases where the excavated rock is used in preparing the sealing materials, it has a positive value because it reduces the cost of consumable materials. In both cases, this should be accounted for in preparing the cost estimate.

7.7.6. Depth of repository

The repositories described so far are normally located at a depth of about 250-1200 metres, depending on the geological conditions and safety issues (human intrusion, radionuclide pathway to biosphere or thermomechanical impact).

7.9. Recapitulation

The major technical factors affecting the cost of a repository are the size of the nuclear programme (*i.e.*, total nuclear electricity production), the scale of the repository, the used fuel management scheme, the type of waste generated, the scope of the cost estimate, the confinement barrier system in the repository and the geological characteristics of the host site. In some projects, other factors are also significant. They are related to the cooling period of the HLW prior to disposal, the operating period, the eventual requirements for monitoring and retrievability, the infrastructure needed, the packaging method, including container type and material, the design of the reception plant, the temperature restrictions in the repository and the design and selection of the sealing systems. The cost of labour and productivity differ between countries.

Chapter 8

NON-TECHNICAL FACTORS OF IMPORTANCE FOR THE COSTS

8.1. Introduction

The management of spent fuel is, in all countries, influenced by a number of social and political factors that concern the management policy, the regulatory process and, not the least, public acceptance of the undertaking. It is clear that in most countries the issue of public acceptance has been and still is perhaps the most important single factor that affects the progress of work on disposal of spent fuel and reprocessing waste. It is also an important factor in most other steps of the nuclear fuel cycle.

Also, spent fuel management is regarded in most countries, not only as a technical/economical issue but also as a significant political issue and thus relies on decisions taken by governments and other political bodies. These decisions have in many cases been strongly related to public acceptance and other social factors. Although these issues are currently common in the countries considered, the differences in approach could be quite substantial between the countries.

This Chapter 8 discusses a number of non-technical, social and political factors affecting the waste management system and, ultimately, the costs. (The importance of financing factors was addressed in Chapter 5.) The following factors are included as examples, but the list could probably be much longer:

- nuclear waste management policy;
- time schedule;
- site selection process;
- licensing process;
- regulatory requirements;
- safeguards regime;
- land price and indemnification;
- taxes;
- public acceptance and political decisions;
- risk factors.

The implication of these factors on the costs could in many cases be quite substantial. However, many of them are unpredictable and difficult to incorporate into a normal cost calculation. The effect of such factors must thus be weighed into a suitable risk factor. In a comparison between different cost calculations around the world, the size of the risk factor applied is very important.

8.2. Social/political factors

8.2.1. Nuclear waste management policy

As explained in Chapter 2, there are two main options for the management of spent fuel: the direct disposal approach and the reprocessing approach. In the former case, the spent fuel is disposed of as such after a certain period of interim storage. In the latter case, the spent fuel is reprocessed and the resultant reprocessing waste, after conditioning and a certain period of interim storage, is disposed of in a final repository.

The choice between these two options involves strategic/political, economic and technical issues. As the strategic/political issues often are the most important, the choice is often decided upon by the government.

From a strategic/political point of view, the long-term assurance of resources and the proliferation issues are most important. In many countries with a planned sustained nuclear programme, the conservation of the natural uranium resource is important and the reuse of the material recovered by reprocessing is given high priority. The proliferation issue is given different weights in different countries. Some countries find it important to reprocess in order to reduce the stock of plutonium by consuming it as nuclear fuel, while other countries oppose reprocessing as it makes the plutonium in the fuel more accessible.

From an economic point of view, the trade-off between the cost of reprocessing with subsequent recycling of the reprocessed material and the cost of fabricating fuel from natural uranium varies with time. Factors influencing the economics are the cost of reprocessing and fabrication of MOX fuel and/or fuel from recovered uranium, and the cost of natural uranium now and in the future.

Finally, some technical factors may be decisive for the choice of option, as some fuel does not readily lend itself to reprocessing and other fuel is not suitable for direct disposal.

As has been explained earlier, the choice of direct disposal or reprocessing will have a significant impact on the costs of spent fuel management and on the disposal of the waste.

8.2.2. *Time schedule*

In most countries, it has been decided that the disposal should be planned to begin after 30 to 50 years of interim storage and no longer. The reason for this is normally ethical in that the people benefitting from the electricity production should also take care of the technology and cost of waste management. Moreover, it is considered important to demonstrate to the public that the waste from nuclear power production can be handled in an appropriate way at a known cost.

In some countries, longer interim storage periods are considered based on the fact that the economics of disposal will improve with time, as a result of decreased costs and the interest earned on the funded money in the meantime. Also, some countries consider the factor of technology development in this case, believing that new and perhaps better methods of treatment or disposal may be developed.

In most cases, the spent fuel or the reprocessing wastes could, from a technical point of view, be kept in an interim storage for a very long period of time, at least a hundred years. The choice of time schedule for the disposal is thus not a truly technical issue, but more or less a political and economic issue.

A delay in disposal will generally reduce the discounted costs. If the delay occurs after the disposal programme has begun, however, it could increase the total cost substantially.

8.2.3. *Site selection process*

The largest problem for the disposal of spent fuel or reprocessing wastes will be to obtain acceptance for a site for the disposal facility. A number of factors will affect this choice of site, *e.g.*, geology, logistics, infrastructure, employment situation, and political majority.

In some countries, a rather long site selection process may be involved. A systematic geological survey of the whole country may be performed, combined with a survey of the other relevant factors. This work will probably include an investigation by drillholes, surface testing and perhaps the sinking of shafts and/or tunnels at two or more sites. In other countries, suitable areas are scarce, thus the choice could be made quickly and the site investigations could be concentrated on that site. The costs for the site selection process therefore vary significantly between the countries. In all cases, the site selection costs have a high economic significance in a discounted cash-flow analysis because they occur in the earlier future.

8.2.4. *Licensing process and regulatory requirements*

As in all nuclear issues, the regulatory requirements and the licensing process differ between countries. In some countries, extensive public hearings are held, while in others the licensing is completed by the authorities without any such hearings. In some countries, all details of the repository must be presented before the licensing process can start, while in others details can be developed and scrutinised by the authorities as the work progresses. These differences will, of course, affect the costs.

8.2.5. *Safeguards regime*

Safeguards have been applied for many years to the interim storage of spent fuel and to reprocessing facilities. Procedures for safeguards required for a repository for spent fuel are presently being discussed within the IAEA [28] and have not yet been established. None of the cost estimates given for spent fuel disposal include any specific costs for post-closure safeguarding of spent fuel in a repository. If properly incorporated in the design of the disposal system, however, this factor should not significantly increase the cost.

8.2.6. *Land price and indemnification*

The cost of land should normally be included in a cost calculation. Clearly, there are great differences between the countries in this aspect. In some densely populated countries the cost might be very high, while in other countries government-controlled land might be used at no cost.

In some countries, when a nuclear installation is built, an indemnification is paid to the local residents, landowners, farmers, fishermen and to the local community as mitigation of the impacts of disposal facilities, according to national and local regulations. The level of indemnification varies considerably.

8.2.7. *Taxes*

In some countries, taxes, grants in lieu of taxes, and other fees could be a substantial part of the costs, while in other countries the construction and operation of the disposal facility could be fully or partly tax-exempt. This will clearly influence the costs.

8.2.8. *Public acceptance and political decisions*

Public acceptance is a major factor in the realisation of a disposal facility and thus has an important impact on the cost, while its impact on the discounted costs may be lower. In the cost calculations, it is normally assumed that the facility will be built as planned and the costs for delays or changes due to poor public acceptance are normally not considered.

Finally, the development of a disposal facility is totally dependent on positive political and regulatory decisions. The costs of a facility could change substantially in an atmosphere of changing political direction. This fact has been experienced in many countries already at this early stage of development of disposal facilities.

8.2.9. *Risk factors*

As is obvious from the above discussion, there are a number of factors that cannot be weighed into a cost calculation in a normal technical way, but must be considered separately. In some countries, this is taken care of in the cost calculation by the use of a separate risk factor that is added to the total cost, to compensate partially for unforeseen changes in the development of the repository programme. In other countries, this factor is not considered, but will be taken care of as an extra cost when it occurs. The approach adopted will clearly affect the results of the cost calculations.

Chapter 9

CONCLUSIONS

In general

Disposal systems: The disposal of spent fuel or reprocessing wastes (high-level waste and alpha-bearing waste from reprocessing) has been studied for some time in all OECD countries with a nuclear power programme. Although the actual disposal of these wastes is not planned to be started until the beginning of the next century at the earliest, the concepts for disposal systems are being developed, and engineering studies and cost estimates have been made.

Scope and goal of the study: In this report, the cost estimates for deep geological disposal of spent fuel and reprocessing wastes performed in some OECD countries have been collected. The costs vary substantially. The goal of the study has been to provide better understanding of the origins of the variations in the cost estimates, and to discuss to what extent various political, institutional, technical and economical factors could explain the variations.

Safety is important: However, it should be recognised that the most important criterion for deciding waste disposal strategies is safety; cost is a minor factor in the decision-making process when compared to safety. There are a number of different approaches to achieve the safety goal.

Disposal cost estimates are still preliminary: Experience of actual construction and operation of the disposal facilities for these wastes is not available and the current cost estimates are, by and large, preliminary. Nevertheless, it should be recognised that many aspects of the cost estimates are based on current experience in nuclear and non-nuclear industries.

Information in this report: The Expert Group reviewed several points to be considered before making cost comparisons and investigated various factors affecting the cost estimates. Some methods for normalizing the cost estimates are discussed. The basic conclusion of the study is that if a clear definition of each disposal project is given, the cost estimates are similar and the differences among the estimates can to a large extent be accounted for.

9.1. The cost estimates to be compared

Compare the cost estimates for similar waste management scenarios: The spent fuel management systems that are adopted or planned in OECD countries are classified into two strategies: direct disposal of the spent fuel and waste disposal after reprocessing the spent fuel in order to recycle the recovered uranium and plutonium. A closer look reveals that there are considerable differences even in the spent fuel management scenarios belonging to one strategy, such as the length of interim storage period. The costs for geological disposal are only a portion of the total costs for spent fuel management. Therefore the comparison of disposal cost estimates that are based on the different spent fuel management strategies or prepared for significantly different spent fuel management scenarios can be misleading if not fully defined.

The scopes of the cost estimates should be standardized: The scope of the published "cost estimates for geological disposal of spent fuel" or "cost estimates for geological disposal of high-level vitrified waste" can differ significantly. Some estimates include costs for transportation of the radioactive waste, some include costs for interim storage as well. The geological disposal costs for other type of radioactive waste, *e.g.*, intermediate-level wastes, are often included in these cost estimates. The coverage of cost components also may differ, for example the cost estimates may include the costs for R&D and site selection (*i.e.*, site screening and evaluation). These differences make it less meaningful to try to compare one cost estimate to another directly.

Undiscounted costs should be compared: Cost estimates may be presented in several ways; *e.g.*, in constant money at a certain defined time, in money developing with time and inflation, or in the present value of money. The difference in the presentation methods drastically affects the resultant numbers because the packaging/disposal will be performed over several decades. For the purpose of financial calculations, the discounted cost estimates are useful. However, for the purpose of international cost comparison, the undiscounted cost is more useful, because the undiscounted figures are much less dependent on the time schedule of the geological disposal and financial assumptions.

Monetary conversion may distort the comparison: Since cost estimates are usually made in national currencies, they must be converted to some common monetary unit before any international comparisons are possible. International cost comparisons are meaningful only to the extent that the currency conversions made are representative of actual cost parities between countries. Temporal fluctuations in the exchange rates can have a substantial influence. A further potential source of distortion is the necessity to use some deflator for the estimates that were originally presented in currency units as of some other date than the base year selected for the comparison. Country-specific indices for different cost components should be used to update the estimates, but the application of such indices would require very detailed information on cost structures and might be very difficult.

9.2. The cost estimates compared in this report

Cost estimates for packaging and deep geological disposal only: For the purpose of this report, the Group decided that the cost estimates which are compared in this report should be those for deep geological disposal and packaging (if necessary). The estimates should not include the costs for interim storage and transportation of the waste outside the repository site. As defined above, in most cases, only spent fuel and reprocessing waste (high-level vitrified waste and alpha-bearing waste) are considered.

Costs for R&D and site selection are not included: The national cost estimates for packaging and geological disposal may include the cost items that are strongly dependent on political and social conditions. Because of the wide variations in the social and economic conditions in OECD countries, the Group decided that it should limit the study to the variations in the technical costs of packaging and disposing of spent fuel and reprocessing wastes. The costs for R&D and site selection are therefore excluded from the costs compared. It should be recognised that those cost items are true costs of implementing disposal and therefore must be included in the analysis of a national disposal strategy.

Costs for R&D and site selection are significantly affected by social/political factors: The costs for R&D and site selection may account for up to 50 per cent of the total costs published. A longer lead time between the time of electricity generation and actual disposal activities, a supplementary research programme for enhancing public confidence, or additional facilities for demonstrating the maturity of disposal technologies will increase significantly the total costs of the disposal programme. These political and social factors strongly influence the actual costs of packaging and disposal.

9.3. Sources of differences in the cost estimates

Considerable variation remains: Even when the scope of the cost estimates is restricted as described above, there is still a wide variation in the cost estimates that have been prepared for spent fuel management systems within each strategy. For instance, the estimated total costs for the direct disposal strategy submitted to the Group show a variation by a factor of 13, mainly because of the large difference in size of the repositories considered.

Uncertainties are not the main cause of the variability: Because the packaging and the geological disposal are future activities, the cost estimates are naturally subject to uncertainties to some extent. However, since many of the basic components of these activities are well known and proven in other areas of the nuclear fuel cycle or in other industries, and since some of the uncertainties in the estimate are accounted for by the application of contingency to the basic cost estimate, any conceptual design of a disposal system can be estimated with reasonable certainty.

A number of factors affect the cost estimates: As discussed in Chapters 7 and 8, there are factors which significantly affect the cost estimates. A detailed study of the cost estimates shows that the factors that may be selected for cost estimates are different. Therefore there is no reason to expect the cost estimates for the geological disposal of the wastes to be similar between the countries or estimates. It is misleading simply to compare the cost estimates without understanding the differences in the various factors underlying them.

Size of the nuclear programme is the most important: The differences found are due to both technical and non-technical factors. Among the technical factors, the size of the nuclear programme and thus the size of the repository is the most important factor affecting the total cost. Also, the kind of waste considered (spent fuel or reprocessing waste) is very important, as well as the need for extra packaging of the waste.

Time schedule of the disposal project is important: Another factor that affects the disposal costs is the timing of the disposal or the cooling period before disposal, since the waste can be packed closer after a longer cooling period at an additional cost for interim storage. The timing of disposal is, however, even more important if financial factors are taken into account, as a delay in the disposal reduces the present value costs for the activities. These factors are explained in the report but are not included in the comparisons made in the study. Other technical factors of importance for the cost estimates include the geological medium chosen and the design of barrier system (including packaging).

Social/political factors are important: As the disposal of spent fuel or reprocessing wastes is a highly controversial political issue in most countries, the social and political issues inevitably affect the costs. They cannot, however, be included as straightforward cost factors in cost calculations, but must be weighed in at the end, for example, as an extra risk factor in the estimates. The social/political issues will, for example, affect the siting and licensing process as well as the overall waste management policy.

9.4. Normalization of cost estimates

Complete normalization is impossible: In order to compare the cost estimates, they must be normalized to specific cost bases in a way that will remove the effect of the most evident causes of differences. Although the relative importance of the factors is given in Table 7.1, their impacts are very difficult to discuss quantitatively. Moreover, a complicated relation exists between the factors, so that it is almost impossible to remove the effect of all the factors completely. However, it is possible to normalize the cost estimates in a way that will compensate for, but not eliminate, the variability caused by some factors.

Normalized costs by electricity generated fall in a relatively narrow range: Four normalization methods are reviewed in this report, all of which are intended to reduce the effect of the differences in the scale of disposal programmes. It is shown that the wide variations in the original cost estimates can be explained by the factors such as the scale of disposal programme, fuel burnup and the amounts of non-high-level wastes. When the cost estimates are proportioned to the amount of corresponding electricity generation, the normalized cost estimates fall in a relatively narrow range. The usual fuel cycle normalization of "per tonne of uranium" does not show a good agreement.

The disposal cost estimates are reasonably well understood: Since the cost estimates were performed independently for different disposal projects and are based on different system designs, the variation of the cost estimates proportioned to the amount of electricity generated is surprisingly small, especially after due consideration is given to the size of the systems (see Figures 6.1 and 6.2). This seems to indicate that the disposal cost estimates for spent fuel and reprocessing waste are reasonably well understood in OECD countries.

9.5. Impacts of uncertainties in the disposal/packaging cost estimates of spent fuel and reprocessing waste

Variation of the estimated disposal cost is not significant for the total electricity generation cost: Several previous studies conclude that the disposal costs of spent fuel and reprocessing waste account for only a few per cent of the total fuel cycle costs in levelised cost calculations. Therefore, a small variation of the disposal cost estimates is not important for the total electricity generation cost.

The uncertainties are not too large to define the amounts of the liabilities: In some countries, disposal cost estimates have been performed to determine the amount of money that must be set aside to fund the estimated cost of future disposal. In these cases, great care has been taken to include contingencies in order to avoid underestimating the future costs. From the present study, one can conclude that the amount of the liabilities can be defined with a reasonable level of confidence.

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Annex I

Countries Annex

BELGIUM

1. General

The Belgian disposal concept presently under study concerns the geological disposal in clay formation of vitrified, medium level and alpha wastes.

The Belgian nuclear power programme consists of seven PWR-type reactors, with a total net capacity of 5.5 GWe. In the reference scenario for cost estimation, the operating life of the nuclear power plants is assumed to be 30 years. The corresponding amount of spent nuclear fuel is 3 530 tU and the corresponding electricity generation is about 1 160 TWh.

In the economic assessments of the geological repository, the wastes mentioned below are taken into consideration:

- Waste from reprocessing plant: it is assumed that all the fuel unloaded from these reactors will be reprocessed abroad and that the waste resulting from these operation will be repatriated.
- Waste produced by the former EUROCHEMIC reprocessing plant: the waste is now stored at the Mol-Dessel site and managed by BELGOPROCESS, a subsidiary of ONDRAF/NIRAS (the "Belgian National Agency for Radioactive Waste and Fissile Materials"). This waste was not included in the calculation of 1 160 TWh mentioned above, but it has only a small impact on the cost comparison.
- Waste from various sources: *e.g.*, nuclear research, medical and industrial applications of radionuclides, daily operation of reactors and manufacture of fuel.
- Decommissioning waste: alpha-bearing wastes originating from the decommissioning of all nuclear facilities (including nuclear power plants) currently in operation.

Table 1. **Distribution of the "B" and "C" waste quantities to be disposed of in the reference production scenario**

Type of waste	Category	Matrix	Volume (m^3)	Volume (%)	Estimated number of primary packages
1. Vitrified VHLW	"C"	Glass	550	2.7	3 050
2. Vitrified VHLW (BELGOPROCESS)	"C"	Glass	200	1.0	1 900
3. HLW (Non-vitrified)	"C"	Concrete	2 600	12.7	2 750
4. Alpha-contaminated MLW/LLW	"B"	Bitumen	5 300	25.9	24 550
5. Alpha-contaminated	"B"	Concrete	11 850	57.8	19 700
Total			20 500	100	51 950

"B" waste: conditioned low- and medium-level waste containing isotopes with a half-life exceeding 30 years.
"C" waste: conditioned high-level waste containing beta-gamma and alpha isotopes.

VHLW: Very-High-Level Waste
HLW: High-Level Waste
MLW: Medium-Level Waste
LLW: Low-Level Waste

The duration of surface storage for cooling varies from one type of waste to another and depends on the heat being emitted. For the vitrified high-level waste, the intended duration is approximately 50 years.

After sorting, processing and conditioning, the resulting volumes of the primary "B" and "C" waste packages considered for disposal in the repository are divided according to their nature, as shown in Table 1. The capacity needed to accommodate the reference waste production programme represents about 750 m^3 of vitrified heat-emitting waste, and about 20 000 m^3 of low and medium-level waste containing isotopes with a half-life exceeding 30 years.

In addition, the geological repository is also being considered to accommodate part of the non-alpha-contaminated low-level waste ("A" waste) of various origins, which would amount to 120 000 m^3. The cost calculation described in this Annex does not include the costs for management and disposal of the "A" waste.

2. Geological medium

The host rock intended for burial of the waste is the Boom clay layer 180 m to 270 m underneath the surface of the Mol-Dessel site. The thermal characteristics of clay limit the number of heat-emitting primary packages that can be buried per area unit. This has a direct influence on the geometry of the disposal facility and on the duration of interim surface storage of this waste. The present tentative design criteria tend to favour a maximum allowed temperature of the clay layer of 170°C in the near field and a maximum design heat load of the repository of 150 kW/ha.

3. Design of repository

3.1. Introduction

Based on the results of the "Safety Assessment and Feasibility Interim Report (SAFIR)" published in 1988, the outline of the architecture of a deep burial facility has been worked out. The geometry proposed for the burial facility is likely to evolve.

3.2. Main principles of the Belgian disposal concepts

With the current stage of knowledges some fundamental technical principles can be considered:

- **Non-reversibility of disposal:** the burial and access galleries will be definitively backfilled soon after disposal so as to restore as closely as possible the same conditions as those prevailing in the undisturbed geological formation.
- **Axial burial configuration:** this means that all waste is placed parallel to the gallery axes. This fully horizontal layout rather than one involving vertical burial wells is mainly imposed by the limited thickness of about 90 m of the clay layer.
- **Segregation of the high-activity, heat-producing waste:** the vitrified waste should be disposed away from all other waste types, in a separate region, to isolate it from any detrimental interference.

3.3. Description of the burial installation

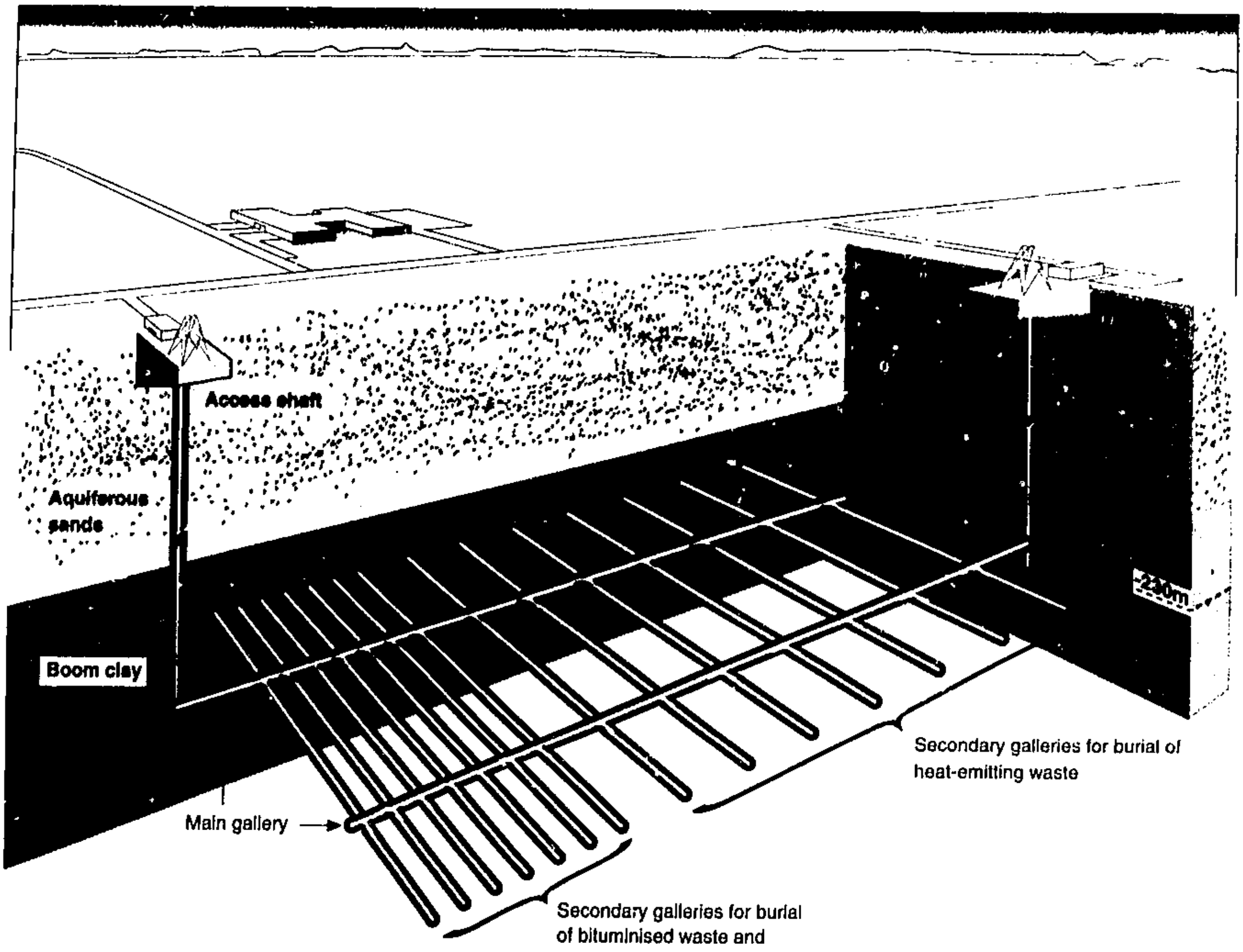
The waste disposal facility will comprise surface installations, access shafts and a network of underground galleries (see Figure 1).

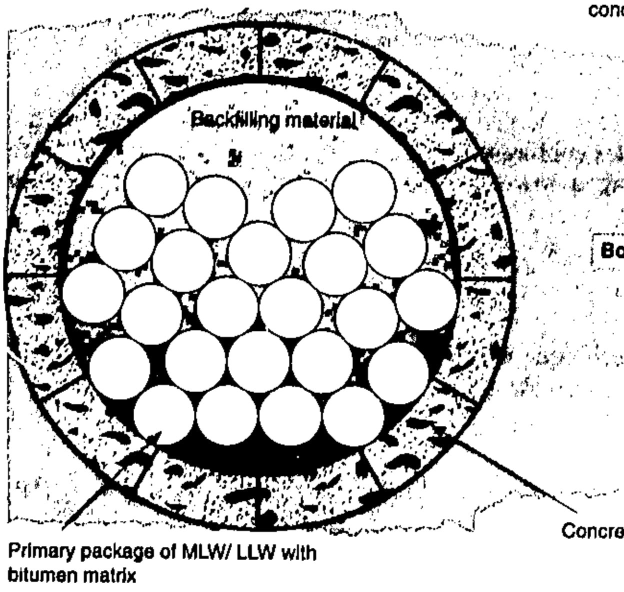
Surface installations: these are composed of units such as acceptance halls for transfer and inspection and buffer storage areas, as well as of units serving the shafts and galleries. The waste is not treated or conditioned on the repository site and corresponding costs are not considered in the cost calculation below.

Access shafts: there will be one main access shaft and probably two secondary shafts of about 6 m in diameter and 250 m in depth, each giving access to the two separate regions, one for vitrified waste and one for high-level, medium-level and alpha-bearing waste respectively.

Network of galleries: the gallery network will be located at mid-depth of the Boom clay formation. In the current concept, it will comprise, in each of the two burial regions, several main galleries of about 3.5 m in diameter, where the waste packages will be handled, and a number of secondary galleries with a useful diameter

Figure 1. **General scheme of the category "B" and "C" waste burial facility according to the axial concept**





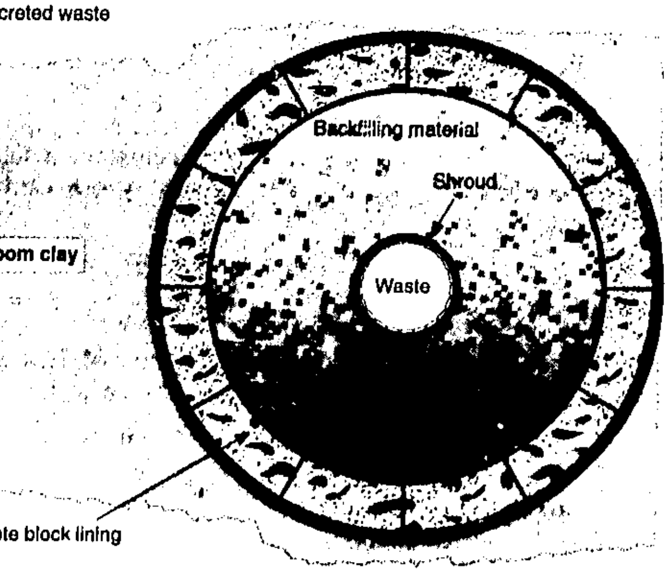


Figure 2. **Axial waste positioning configuration: primary package of MLW / LLW embedded in a bitumen matrix**

Figure 3. **Final arrangement of disposal gallery for high activity vitrified waste (cross-section)**

of 2 m, where the waste packages will be buried, and which will be excavated perpendicular to and along both sides of the main galleries.

The length of each secondary gallery is presently assessed to be 200 m to 300 m for the vitrified waste region, and about 800 m for the non-heat-producing waste. The galleries will be circular in cross sections and lined with concrete blocks. The distance between secondary galleries will be about 50 m on average.

The total excavated clay volume is estimated to be 235 000 m^3, of which the secondary galleries account for about 100 000 m^3.

For the non-vitrified waste, after the waste packages have been placed in the secondary galleries, the remaining voids will be filled with a backfilling material that remains to be decided on. One option would be to reuse excavated clay. Figure 2 shows an example of an axial waste-positioning configuration of waste drums coated with bitumen or with concrete. It has been decided not to use any overpacks in order to minimise hydrogen formation originating from corrosion, which could be detrimental for the long-term behaviour of the clay barrier.

For high-activity vitrified waste, only one glass canister will be placed in each cross section, for reasons relating to thermal load (see Figure 3). A thin metal shroud surrounding the glass canisters in the disposal galleries, as well as an annular backfilling material outside the shroud, is installed in advance of the waste. The characteristics of the shroud and backfilling materials will be defined during the ongoing R&D phase of the project.

The main galleries will remain open throughout the waste burial operations. At the end of these operations, the galleries will be filled, after which the part of the shafts located in the clay will be dismantled and sealed.

3.4. *Time schedule*

The present reference scenario used in the economic studies is based on the following assumptions:

- 2015 start of the detailed study of the industrial facility;
- 2020 start of the construction of the underground burial installation;
- 2035 start of burial of non-vitrified waste;
- 2050 start of burial of vitrified waste;
- 2070-2080 closure phase of the site.

4. Results of cost calculations

4.1. *Purpose of the cost calculation*

The cost calculations are used for determining the fees charged to the waste producers for financing the burial activities (see Section 6). The cost calculation includes contingencies (50 per cent) and some conservatism is introduced in the cost per unit volume by considering a low-side assumption for the waste production programme.

4.2. *General assumptions*

The methodology used is based on the cash flow technique in constant currency units. The cost calculations is based on the construction and operation techniques available today. The calculation also assumes today's regulations.

4.3. *Results*

Table 2 presents the result of a cost estimate for the reference scenario, with contingencies (50 per cent), and for a reference set of cost assumptions. The cost estimate is performed in 1990 economic conditions and presented in the price level of 1990 (million ECU). This result is without discounting.

In that table, the costs for R&D comprise preparation of a prototype disposal facility, a concept and safety design, project management and engineering studies. (Table 3 shows the structure of the R&D expenditures). The construction costs comprise construction of surface and underground facilities (including site service facilities).

Table 2. **Cost estimate[a] for deep geological disposal**

Nuclear capacity of 5.5 GWe with 30-year operation

Cost Category	Cost estimates (M ECU of 1990)
R&D	150
Construction	450
Operation and backfilling	195
Decommissioning	30
Total	825

a) No discounting is done. Contingency allowances of 50 per cent are included. Overpacking is not considered in the strategy assumed in the cost estimate.

The material for backfilling the disposal holes and filling the galleries and shafts is included in the operation and backfilling costs.

The cost estimate includes the costs for R&D, construction of the facilities, operation, decommissioning, sealing, etc. The estimate includes the costs both in the past and in the future. The costs for site selection are not included because it is assumed that the repository will be built at the Mol-Dessel site.

The global cost with contingencies is estimated to be 825 M ECU in constant currency of 1990 as presented in Table 2. The cost estimate that is compared to other estimates in the main text of this report, 675 M ECU, excludes the costs for R&D.

Table 3. **Structure of R&D expenditures**

Cost item	Contribution (%)
Prototype	55
Concept + safety	5
Project follow-up	15
Engineering studies	25
Total	100

4.4. Uncertainty factor

Sensitivity studies are performed in order to assess the uncertainty range and thus the risk of underestimating the actual costs. The results of the sensitivity studies are used to determine an uncertainty factor to be applied directly to the cost estimates. This approach was preferred to the use of contingencies applicable to specific items.

Various parameters important in defining a burial scenario are treated in the sensitivity studies. Table 4 provides results of a sensitivity analysis on the duration of the NPP operation and on the amount of decommissioning waste.

Table 4. **Sensitivity of total undiscounted cost to the operating time of nuclear power plants and to the inclusion of the decommissioning waste**

Variation in % from reference case

Operating time (Years)	Decommissioning waste	
	Included	Excluded
20	-15	-19
30	Reference	-5
40	+13	+8

5. Specific results

The total cost estimate given in Table 2 is 825 M ECU with 50 per cent in contingencies. It should be noted that the figure includes the costs for R&D. When these costs are reduced from the total, the estimate becomes 675 M ECU, corresponding to 191 ECU/kgU or 33 000 ECU/m^3 of waste or 0.0006 ECU/kWh.

6. Financing system

In Belgium a national agency, ONDRAF/NIRAS, is responsible for the final disposal of radioactive waste. Each time that waste is handed over to ONDRAF/NIRAS, payments are made by the waste producer to the agency. These fees are used to maintain a fund to finance the whole scope of burial activities from R&D until final site closure. The fee for each waste category is derived from the cost assessment and the uncertainty factor resulting from a sensitivity analysis.

For example, a current fee for high-level vitrified waste is 235 000 ECU/m^3. Revision of the fees is triggered by updated information on the basic data defining a burial scenario.

The level of the fund will vary due to:

a) the credit:
  - the contributions resulting from the tariff applied at the time of waste collection by ONDRAF/NIRAS;
  - the interest from revenues from investment of the available amounts of the fund;

b) the debit:
  - the withdrawals made to finance the expenses related to the realisation of the waste disposal programme.

ONDRAF/NIRAS guarantees the economic and accounting transparency of the costs and charges related to disposal; and is bound to make and present an annual report to the waste producers who contribute to the fund, on the technical and financial management of the waste disposal programme.

CANADA

1. Boundary conditions

In Canada there are currently 18 reactors in full operation, 2 in the process of start-up, and 2 under construction. The total gross generating capacity of the 22 reactors is 16 343 MWe. They are Canada Deuterium Uranium (CANDU) pressure tube reactors, moderated and cooled by heavy water and fuelled with natural uranium in the form of uranium dioxide (UO_2).

The average burnup of fuel is assumed to be 684 GJ/kgU (7 900 MWd/tU), although this is being increased through fuel management strategies. Following their removal from the reactors, the fuel bundles are stored in water-filled storage bays at the reactor sites. After a cooling period of at least five years, the bundles are rearranged to increase their storage density in the bays or are sealed in containers and stored in air-cooled concrete canisters.

At the beginning of 1991, there were 753 884 spent fuel bundles containing 14 348 Mg of elemental uranium in storage in Canada. At the current rate of production, 67 700 spent fuel bundles containing 1281 MgU are added each year.

2. Geological conditions

The geological medium being given the most attention for disposal of nuclear fuel waste in Canada is the plutonic rock of the Canadian Shield. The primary focus of the R&D programme on final disposal is on the granitic and gabbroic plutons because of their relative abundance in the Shield (about 75 per cent and 15 per cent respectively).

The primary characteristics of the plutonic rock masses of the Canadian Shield relevant to disposal are that it is generally moderately fractured with planar zones of high fracture frequency, and it is saturated with groundwater to within a few metres of the ground surface. The regional topographical gradients are low (typically about 1 m/km), and the groundwater chemistry is saline at disposal depths.

3. Waste management system

3.1. Overview

At present in Canada no group has been given the mandate to site or construct a nuclear fuel waste repository. AECL Research and Ontario Hydro currently have a mandate to complete the Canadian Nuclear Fuel Waste Management Program (CNFWMP). The program has been established to develop and demonstrate the technology for safe storage, transportation and geological disposal of spent fuel or reprocessing waste. AECL Research is responsible for its disposal. The program began in 1980 and is currently undergoing a formal regulatory, technical and public review.

At this time in Canada, reprocessing is not considered economically feasible and spent fuel disposal is the reference case. In the CNFWMP concept for direct disposal, the fuel bundles discharged from a reactor are stored at the reactors for 10 years and are then transferred directly to a disposal facility. This spent fuel age of 10 years out of reactor is a very optimistic estimate and provides for an "extreme" case for the facilities design from a radiation and heating perspective. The actual time from reactor discharge to disposal may be at least 20 years.

AECL Research made a projection of future accumulation of spent fuel to establish the capacity specification for the conceptual design of a disposal centre. It was estimated that 10.1 million spent fuel bundles containing 191 133 MgU would be produced by the year 2035 using an optimistic growth rate for nuclear electric generating capacity in Canada.

The cost data given below is taken from a conceptual design for a disposal centre based on this capacity estimate [1]. The conceptual design assumes the disposal of spent fuel in a repository excavated at 1 000 m depth in an unspecified granitic pluton. The spent fuel will be shipped from the nuclear generating stations to the disposal centre, where it will be sealed in corrosion-resistant containers and emplaced within an engineered sealing system in the repository at the rate of 3 471 containers (249 912 bundles) per year. The assumed period of operations is 41 years. When filled to the specified capacity, the repository will be sealed and the surface facilities will be decontaminated and decommissioned.

3.2. Spent fuel encapsulation concepts in the CNFWMP

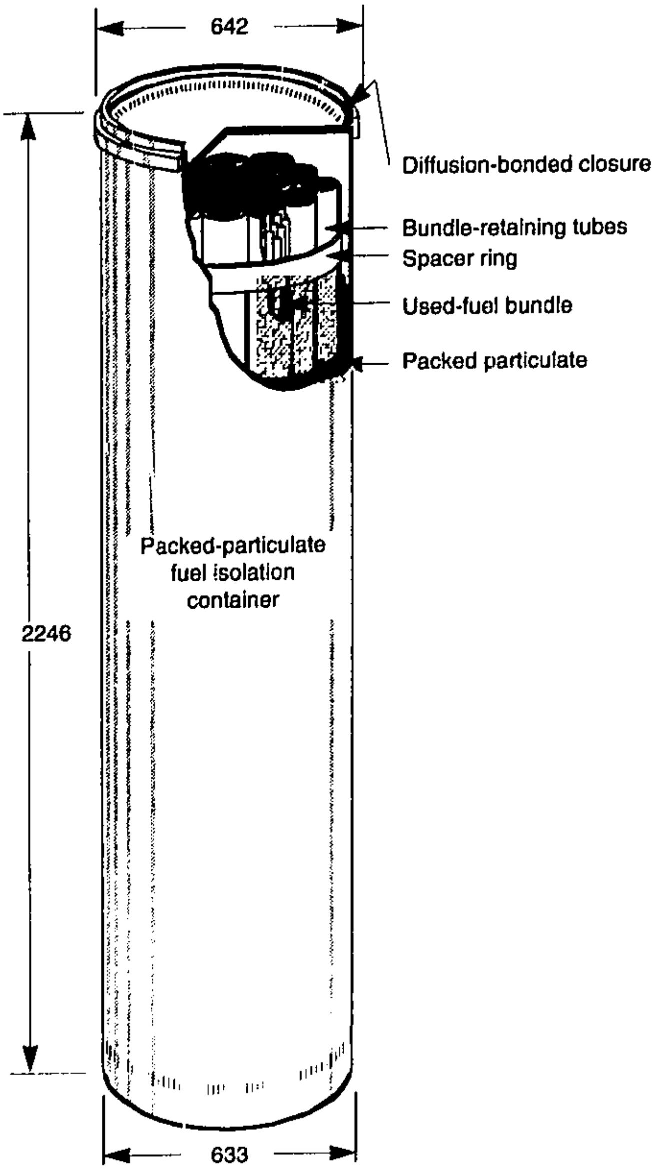
CANDU reactors are fuelled with natural UO_2 pellets, about 12 mm in diameter and 15 mm long, hermetically sealed in Zircaloy-4 tubes about 50 cm long, called elements. For ease of handling, the fuel is assembled in bundles comprising either 28 or 37 elements, depending on the reactor in which it is used. A bundle is about 10 cm in diameter, 49.5 cm long and has a mass of about 25 kg (about 19 kgU).

The spent fuel bundles are sealed in disposal containers. The container is required to be structurally durable for a period of 500 years after emplacement, and to withstand external pressure of 10 MPa from hydrostatic head and 1 to 3 MPa from the swelling of clay-based sealing materials at a temperature of 100°C. The container will hold 72 CANDU fuel bundles. For the conceptual design study, a thin-wall packed-particulate container fabricated of 6.35-mm-thick Grade 2 titanium (Figure 1) was selected, although copper canisters are also being considered.

The packaging plant, co-located with the repository, will provide for receipt of spent fuel, sealing of the fuel bundles in corrosion-resistant containers, and transfer of the containers to the repository shaft. Spent fuel will be received at the packaging plant in either a road or rail transport cask containing two to six storage/shipping modules. The spent fuel will be unloaded from the transportation casks and may be temporarily held in a receiving surge-storage pool.

The shipping modules will be transferred by a remote-handling system to a hot cell, where the spent fuel bundles will be removed from the shipping modules and inserted into a disposal basket. In the transfer operations, each bundle will be identified to comply with safeguards requirements. Seventy-two spent fuel bundles will be loaded in a basket, giving a nominal container heat load of about 300 W for fuel 10 years out of reactor. The

Figure 1. **Thin-walled fuel disposal container**



loaded basket will be placed in a titanium disposal container. All void space in the container will be filled with a particulate, such as glass beads, that will be vibrationally compacted to a sufficient density to support the container shell against the expected external hydraulic and mechanical loads. The top head will be installed on the container and sealed with a diffusion bond. Following nondestructive testing and decontamination, the disposal container will either be transferred to a headframe surge-storage pool or loaded into a container cask and transferred to a container cask laydown area in the repository shaft headframe.

Additional supporting site-service installations will supply the process utilities, waste treatment, trades, stores and warehousing, administration and management needed to operate the encapsulation plant

3.3. The CNFWMP repository concept

The reference disposal centre design developed as a case study in the CNFWMP [1] shows the repository constructed in a granite pluton. It has a minimum plan area of about 2 km by 2 km and is at a depth of 1 000 m (Figure 2). Five vertical shafts connect the surface facilities to the disposal level: two upcast ventilation shafts, a downcast ventilation shaft, a service shaft and a waste-handling shaft. The total estimated excavated volume of rock is 7 215 330 m^3.

Access to the repository disposal area is provided by perimeter tunnels and two central access tunnels that divide the disposal area in half. Each half is operationally separated and, when completed, will have four panels. Container emplacement and disposal room sealing take place in a panel on one half of the repository, whereas panels of disposal rooms for future use are excavated and serviced on the other side.

The underground facilities will provide for the transfer of containers in shielding casks to the disposal area, for the emplacement of containers into prepared disposal boreholes and for the subsequent sealing of the boreholes, the disposal rooms and the tunnels and shafts. Systems for preparing the sealing materials will also be provided.

For transfer to the repository, the used fuel container will be loaded into a 35-Mg shielding container cask in the packaging plant and transferred underground using the conveyance in the dedicated waste-handling shaft.

In the disposal room having a maximum capacity of 282 containers, a vertical borehole in the floor will be prepared to receive the disposal container. The borehole will have a diameter of 124 cm and a depth of about 500 cm. The centres of the boreholes will be spaced about 210 cm apart to ensure that neither the maximum container outer-surface temperature, nor the maximum buffer temperature of 100°C, is exceeded. Prior to receipt of the container, the reference clay-based buffer material (*i.e.*, 50 per cent sodium bentonite clay and 50 per cent silica sand by mass) will be compacted into the borehole. This will then be axially augered to provide a hole 74 cm in diameter and about 280 cm deep for receiving the container. Following container emplacement, the gap between the container and the buffer will be filled with sand.

Once the container has been lowered from the container cask into the prepared borehole, the empty cask will be returned to the surface for reuse. Additional buffer material will be placed and compacted over the container to the disposal room floor level.

The disposal room will be backfilled by placing and compacting the reference clay-based backfill material mixture (*i.e.*, 25 per cent glacial lake clay and 75 per cent crushed granite by mass) to fill the lower portion of the room. The upper part of the room will be filled by pneumatic placement of a backfill material similar to the buffer. A concrete bulkhead will be constructed at the room entrance to complete the room sealing.

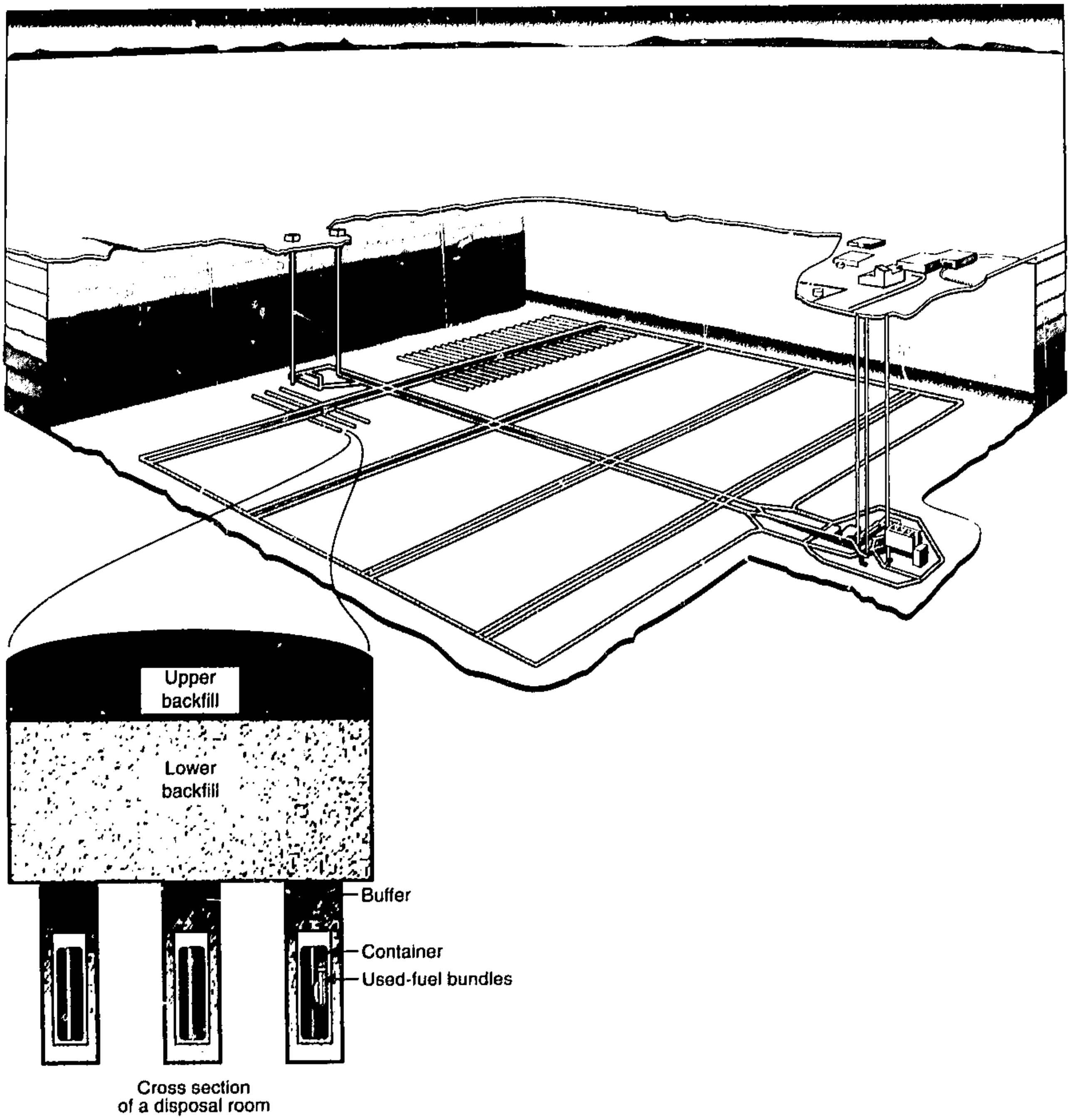
The sequence of room excavation, *i.e.*, borehole drilling and preparation, waste container emplacement, borehole sealing and room backfilling and sealing, will continue throughout the operating life of the repository. The rooms will be developed in a retreat sequence from the exhaust ventilation shafts toward the access shafts.

The surface facilities for the repository will be those needed to prepare the sealing material components, such as an excavated-rock-crushing plant, a concrete-batching plant, and a buffer and backfill preparation plant. Additional supporting site services will supply the process utilities, waste treatment, trades, stores and warehousing, and administration and management needed to operate this centre.

When the repository is filled and a period of monitoring has provided the public and regulators with sufficient confidence to authorise vault closure, the access tunnels and shafts will be backfilled and sealed, and the surface plant will be decontaminated and decommissioned. This site will be returned to a state suitable for public use and identified with permanent markers to indicate the repository location.

The design conditions for the repository assume the emplacement of 140 256 containers of spent fuel 10 years after discharge from the reactor, representing a total heat loading of about 14.1 W/m^2 in the loaded area of each panel and about 10.4 W/m^2 for the entire repository (assuming a square shape).

Figure 2. **Reference disposal vault design with borehole emplacement of used-fuel containers**



4. Resuts of cost calculations

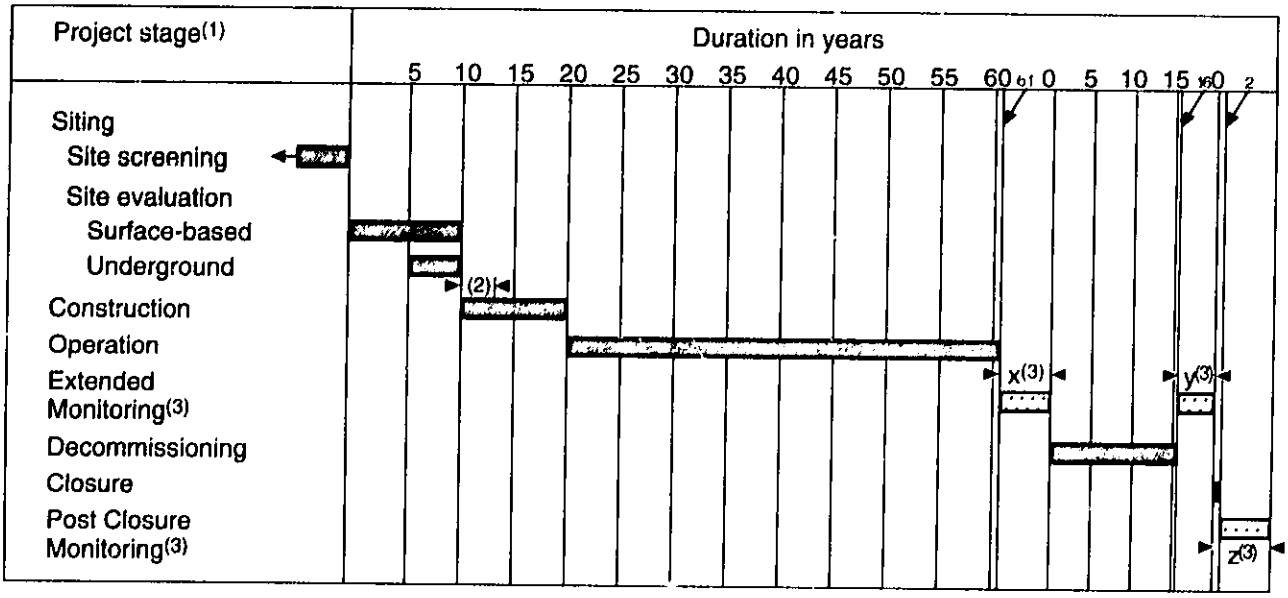
4.1. Purpose of cost estimates

The cost estimate presented below is from the spent fuel disposal centre study done within the CNFWMP. The information is being used in the review of disposal technology and also provides a base case for comparing the costs of alternative components of the disposal system. These data, after being adjusted, are also used by some Canadian utilities as the basis for the cost calculations to determine the charge for waste disposal that should be included in the total charge for the sale of electricity.

4.2. Assumptions for CNFWMP disposal centre study

The cost estimate has been calculated in constant 1990 Canadian dollars and distributed over time on the schedule shown in Figure 3. The estimate does not consider any particular site conditions. The construction and operation costs are estimated assuming that current codes, guidelines and standards must be satisfied and that currently available technologies are applied. The costs have been estimated using relevant experience from mining, geotechnical, mechanical and nuclear engineering. Where there was no analogous experience, the opinion of experts has been used as a basis for costing.

Figure 3. **Used-fuel disposal centre master schedule**



1) The schedule does not allow for delays in obtaining work approvals/ authorisations and licenses.
2) Three years of Performance Testing and Design Refinement.
3) Monitoring periods of undefined duration that are not required by disposal concept.

The schedule and cost estimate do not include the time required by the approval process for implementing each stage of disposal centre development because the process has not been defined. The estimate includes the cost of developing one panel of disposal rooms and parts of two others in the construction cost. The development of the balance of the rooms, the emplacement of all disposal containers and the sealing of all rooms are included in the operating costs.

4.3. Results of cost calculations

The results of the cost estimate are given in Table 1 by the stages of the disposal centre project as given in Figure 3.

Table 1. **Summary of estimated costs for a used-fuel disposal centre**

1990 M $Canadian

Project stage	Surface facilities	Repository	Total
Siting (Screening and evaluation)			805.0
Construction	1 005.5	723.5	1 729.0
Operation	3 928.3	3 130.1	7 058.4
Decommissioning and sealing	221.6	525.7	747.3
Total	5 155.4	4 379.3	10 339.7

The estimated cost for nuclear fuel waste disposal is strongly influenced by major elements in the disposal system design. As an example of the significance of these factors, the costs of the thin-walled packed-particulate titanium disposal containers, and the sealing materials and systems associated with clay-based seals are given. For the reference disposal system design described in this Annex, the estimated costs of these components are shown in Table 2.

Table 2. **Estimated costs of specific components**

1990 M $Canadian

Component	Estimated costs		
	Surface facilities	Repository	Total
TWPP basket and container[a]			
- Fabrication cost	2 249.3	–	2 249.3
Clay-Based Seals			
- Buffer material cost	–	1 272.4	1 272.4
- Backfill material cost	–	563.6	563.6
- Underground preparation plant	–	31.4	31.4
Total	2 249.3	1 867.4	4 116.7

a) TWPP: Thin-Walled Packed-Particulate.

It is useful to assess the sensitivity of disposal system costs to major disposal system design decisions. We cannot make this analysis now because a cost estimate for a disposal system containing an alternative system(s) has not been completed.

4.4. Contingencies

To account for the level of detail in the cost estimate and the uncertainties in the development of costs for individual elements, a 17 per cent contingency has been applied. As well, the uncertainty of the final result is expressed as a confidence level applied on the basis of the expert opinion of the cost estimators: the estimate may be as much as 15 per cent too high or 40 per cent too low.

5. Presentation of the costs of disposal

The constant currency cost estimate presented above, totalling Canadian $10 339.7 M, corresponds to Can $54.1/kgU or Can $9.6 M/m^3 of waste or Can $0.9491 M/TWh or Can $1 433/m^3 of excavated rock. It should be noted that the total cost (Can $10 339.7 M) includes the costs of site screening and evaluation (Can $805 M), which are not included in the ''total cost'' (rounded to Can $9 500 M) quoted in the main text

6. Financial analysis of disposal costs

The utilities in Canada that generate nuclear electricity do cost calculations to determine the fee that must be included in the selling price of electricity in order to collect adequate funds to pay for nuclear fuel waste disposal. Some of these calculations are based on the cost estimate presented above but are scaled for the mass of spent fuel that is currently planned by the utility. Appropriate financial calculations are then applied to account for the time between the collection of funds and the implementation of disposal.

As an example, Ontario Hydro is currently basing their cost calculations on 5 million bundles of spent fuel. They are collecting a fee now on the electricity generated that is based on the implementation of disposal in 2025. The present value of disposal of spent fuel on that schedule is $0.00066/kWh. These funds are assumed to earn interest at the rate of annual inflation +3 per cent. The funds are used to pay part of the R&D costs and will pay for all the costs of siting, construction, operation, and decommissioning and sealing of a repository.

Reference

1. *Used-Fuel Disposal Centre - A Reference Concept,* Unpublished Contractor's Report No. TR-M-3*, AECL CANDU in association with J.S. Redpath Limited, Golder Associates and The Ralph M. Parsons Company, [Unrestricted, unpublished contractor's report available from Scientific Document Distribution Office (SDDO), Atomic Energy of Canada Limited, Research Company, Chalk River, Ontario, Canada KOJ 1JO].

FINLAND

1. General

The Finnish nuclear power programme consists of four reactors located at two sites. Teollisuuden Voima Oy (TVO) operates two BWR units, TVO I and II (2 x 710 MWe), at the Olkiluoto site. The units were commissioned in 1978 and 1980. Imatran Voima Oy (IVO) operates two PWR units, Lo1 and Lo2 (2 x 445 MWe) at the Loviisa site. They were commissioned in 1977 and 1980.

IVO has an agreement with its Soviet fuel supplier to return the Loviisa spent fuel to the Soviet Union. Consequently, the Finnish plans for the final repository of spent fuel concern only the spent fuel of the Olkiluoto power plant. The strategy adopted for the management of the spent fuel is direct disposal after a period of interim storage. Other wastes are not assumed to be disposed of to the repository.

The estimated lifetime of the Olkiluoto reactors is 40 years. The corresponding electricity production from the two units is calculated to be about 430 TWh. The estimated total amount of spent fuel from 40 years of operation is considered to be 1 840 tonnes of uranium. The average burnup of the fuel is approximately 35 000 MWd/tU.

2. Geological medium

The final repository for the spent fuel is planned to be constructed in the Finnish crystalline bedrock at a depth of several hundred meters. Since 1987, deep drilling and other field investigations to select a final repository site have been under way at five candidate areas. The results have shown that it is probably possible to find in the Finnish bedrock numerous areas where a safe final repository for spent fuel could be constructed. The site will be selected by the year 2000.

3. Waste management system

3.1. Overview

The low- and intermediate-level operating wastes will be disposed of in underground repositories constructed at the power plants. The excavation of TVO's repository at Olkiluoto (the VLJ Repository) started in 1988 and it will be commissioned in 1992. It consists of two silos constructed at a depth of 70-100 meters in crystalline rock. At a latter stage, the repository will be enlarged for decommissioning wastes. IVO has postponed the construction of the repository at Loviisa due to minor waste quantities and a large storage capacity.

The spent fuel of Olkiluoto is transferred, after a period of storage in the reactor pools, to the interim storage facility (the KPA Store) located at the power plant site. The storage facility began operating in 1987. The KPA Store is a water-pool-type storage facility and has at present a capacity of 1 200 tonnes of uranium and can be extended if necessary.

The spent fuel will be stored in the water pools for 20-40 years. The fuel will then be transferred to an encapsulation facility collocated with the final repository.

3.2. Site services

For the operation of the encapsulation plant and the final repository, various auxiliary facilities are necessary at the site. Most of the buildings and facilities for site services are located in the area of the encapsulation plant (Figure 1), which is 500 m x 740 m. The upper ends of three shafts are also inside this area.

In connection with the encapsulation station, there are offices and other facilities for staff. In the plant area there are buildings for workshops, water plant, heating station, bentonite handling, vehicle service, drain-water purification, fire station, canteen, transformer and storage of goods. Buildings for rock crushing and areas for excavated rock and crushed rock are also in the same plant area. Near the main gate there are areas for parking and temporary accommodation, as well as a shop.

The operations staff is estimated at about 100 persons, including administrative personnel at the site. Their costs are included in the operation costs of both the encapsulation facility and the repository.

3.3. Encapsulation facility

An encapsulation plant will be located on the ground surface at the repository site. A cold process is used to encapsulate the spent fuel bundles. The encapsulation facility is dimensioned to accept about 140 tonnes of fuel per year (capacity factor of 100 per cent). The total building volume of the plant is 90 000 m^3.

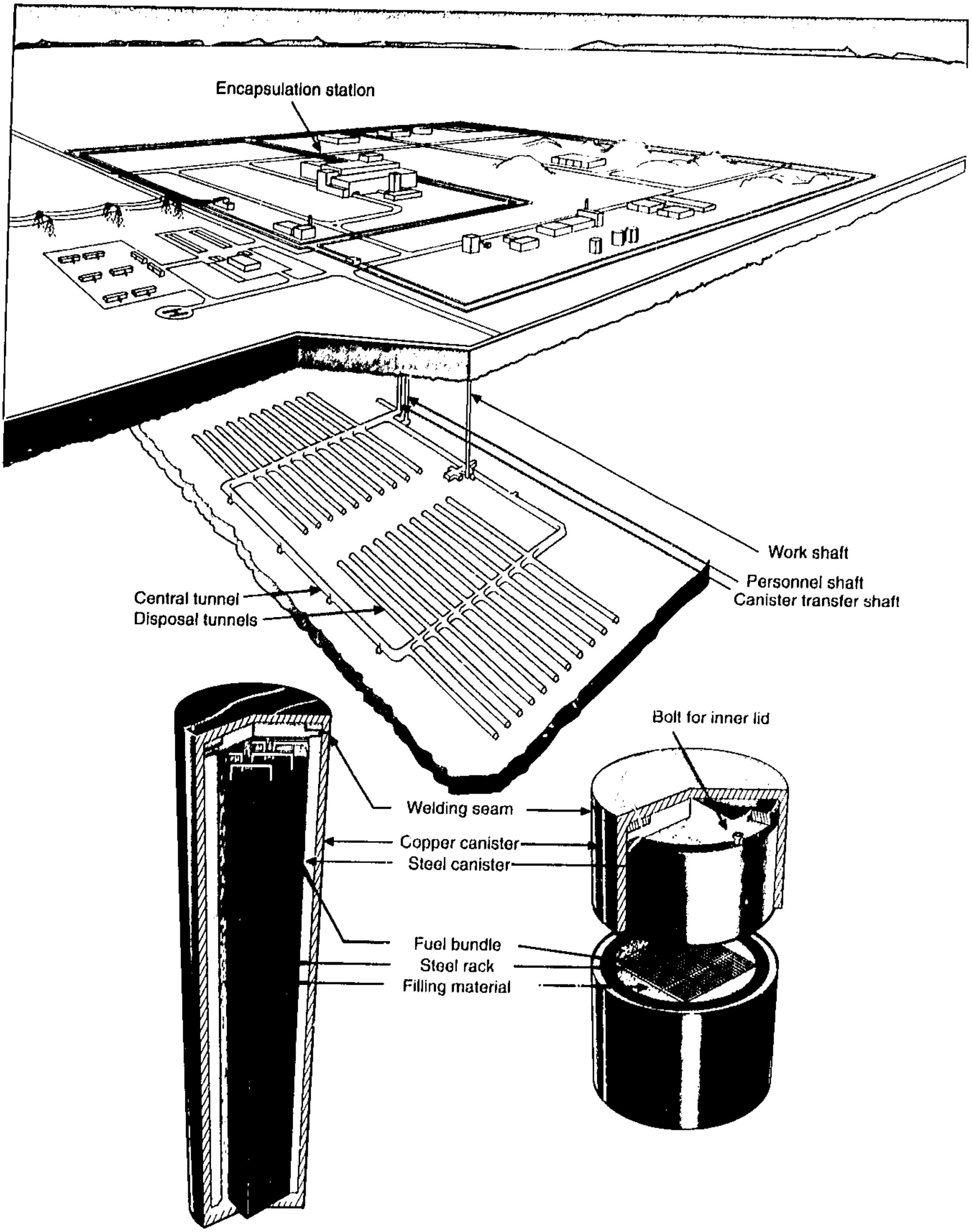
Fuel bundles are encapsulated in copper-steel canisters (see Figure 1). The canister is a cylinder 4.5 m long and 80 cm in outer diameter. It has a wall thickness of 10 cm (5 cm of copper, 5 cm of steel) and can accommodate nine bundles. Solid granulates, *e.g.*, lead shots, are used as filling material for the canisters. The structure consists of a steel canister as a load-bearing element, with an outer corrosion shield of copper. The total power of a canister at disposal shall not exceed 1 200-1 400 W (depending on burnup and cooling time) in order to keep the temperature on the surface of the canister below 100°C. The total number of canisters is 1 150, corresponding to 1 840 tonnes of uranium.

3.4. Final repository

The repository will be constructed at a depth of several hundred meters (*e.g.*, 500 m) in crystalline bedrock. The waste canisters are deposited in vertical holes (1 150 holes) in the floors of the horizontal disposal tunnels. The distance between the vertical holes is 6 m. The repository area is 440 m x 860 m, of which the disposal tunnels take 250 m x 860 m. Tunnels are connected to the surface with three vertical shafts. The total excavated rock volume is 240 000 m^3, of which the disposal tunnels (8 400 m) account for 120 000 m^3. An artistic impression of the repository is shown in Figure 1.

The buffer material in the vertical disposal holes is highly compacted bentonite. The disposal tunnels are filled during the operations phase with a mixture of sand and bentonite directly after the canisters are emplaced in the holes. Finally, the central tunnels and shafts are filled with the same material. The maximum allowed temperature of bentonite on the surface of a canister is 100°C and this condition restricts the maximum heat load

Figure 1. **Final repository for spent fuel and structure of copper-steel canister**



per canister. The resulting maximum design heat load of the repository is about 70 kW/ha The estimated total heat generation is 1 500 kW at the time of emplacement.

3.5. Time schedule

According to the schedule confirmed by the government, the final spent fuel repository should be constructed in the 2010s and commissioned by the year 2020. The operation period is about 20 years. The repository will be closed soon after the canisters have been emplaced. The retrievability of the canisters is not considered in the repository plan.

In the years 1980-2010, comprehensive R&D work, as well as site characterization and selection, is performed. The costs for these activities are included in the cost estimate.

According to the Finnish legislation, the responsibility for the waste is transferred from the utility to the State after the repository has been sealed. With a view to the possible future monitoring and survey of the repository site, a separate supervision charge must be paid to the authorities. This charge is included in the cost estimate.

4. Results of cost calculations

4.1. Purpose of the cost calculation

The cost estimate was performed primarily to provide a basis for determining an adequate fee to be levied on nuclear power production for financing the back-end activities. The cost estimate is updated annually. In order not to underestimate the fee, the cost calculations are deliberately made in a very conservative way.

4.2. General assumptions

The cost calculation is based on the construction and operation techniques available today. The calculation is also performed according to today's regulations.

4.3. Results

The cost estimate for direct disposal of TVO's spent fuel is shown in Table 1. The cost estimate was prepared in 1990 and presented in the price level of December 1990 (million Finnish Markka). No discounting has been done.

The cost estimate includes the costs for site selection and R&D, construction of the facilities, operation, decommissioning and sealing, etc. The estimate includes the costs both in the past and in the future; *i.e.*, from the year 1980 until the repository is sealed.

Table 1 **Cost estimates for encapsulation and final disposal of TVO's spent fuel**

Price level of December 1990

Cost item	Cost estimate (M FIM)
Site selection, R&D	530
Investments	
- Encapsulation plant	470
- Final repository	430
Operation	
- Encapsulation plant	1 310
- Final repository	490
Decommissioning and sealing	
- Encapsulation plant	30
- Final repository	170
Other costs (administration, authorities, etc.)	320
Total	3 750

The costs for site selection and R&D comprise site investigations, safety studies and assessments in different stages and development of encapsulation and repository technology. The investment costs comprise detailed planning (preparation of the documents for licensing) and construction of facilities. Prefabricated canisters have been included in the operation costs of encapsulation plant. The buffer material for disposal holes and filling of disposal tunnels is included in the operation costs of the repository. The supervision charge for future monitoring and survey is included in the other costs.

The cost estimate, which is compared with other estimates in the main text of this report and excludes the costs for site selection and R&D, is 3 220 million Finnish Markka.

4.4. *Contingencies*

The basic cost estimates for future costs of final disposal are drawn up in a conservative way. Furthermore, in order to avoid underestimation of the fee to be levied on nuclear power generation, each cost item includes a contingency allowance for unforeseen costs and uncertainty in the estimate. These contingencies for the estimates of future costs vary between 15 per cent and 20 per cent depending on the accuracy of the plan, being on the average 19 per cent.

5. Specific results

The total cost estimate given in Table 1, 3 750 M FIM, corresponds to 2 040 FIM/kgU or 1.4 M FIM/m^3 of waste or 0.009 FIM/kWh. It should be noted that these figures include the costs for site selection and R&D. When these costs are excluded from the total, the unit cost becomes 1 750 FIM/kgU.

6. Financing system

The Finnish utilities make financial provisions for the future costs of nuclear waste management. An updated cost estimate covering spent fuel, low- and intermediate-level wastes and decommissioning has to be presented to the authority annually. On the basis of these estimates, the Ministry of Trade and Industry each year confirms a fee to be paid by the utilities to the State Nuclear Waste Management Fund. The fund is set up for each utility company and administered by the government.

The fee is adjusted in such a way that the contributions paid into the Fund will cover all future costs of waste management (including management of all the produced wastes and decommissioning) by the 25th year of plant operation even if the plant would then be shut down and no more fees could be collected. Until that time the power companies must furnish securities for the outstanding liability, *i.e.*, the estimated future costs not covered by the contributions paid into the Fund.

In the 1990 estimate, which is calculated according to the principle described above, the total future costs for management of TVO's wastes produced by the end of 1990 are 3 832 M FIM. Of this, about 2 300 M FIM is attributable to final disposal of spent fuel. TVO's present deposits (March 1991) in the Fund are 1 903 M FIM. A significant part of the annual fee, which is currently about 300 M FIM, is covered by the interest on the Fund. It should be noted that the fee is calculated on the basis of undiscounted costs.

The corresponding cost estimate for IVO is 1 103 M FIM and the deposits are 585 M FIM.

FRANCE

1. General

The policy in France for final disposal of radioactive waste calls for isolation of high-level vitrified waste (HLW) and transuranic waste (TRU) in deep geological formations. Both waste types originate from the reprocessing of nuclear fuel, which is the strategy adopted for spent fuel management.

In the years to come, the main source of the waste will be the new COGEMA reprocessing plant in La Hague. By the year 2010, the total quantity of waste stored on surface will be around 130 000 m^3 for TRU waste and 4 000 m^3 for HLW. At that time, the annual production of waste based on the nominal capacity of all reprocessing plants will be respectively 4 000 m^3 and 200 m^3 (equivalent to the waste arising from reprocessing of the spent fuel from 370 TWh electricity generation). These quantities do not include the 30 000 m^3 of short-lived waste produced annually and disposed of in surface facilities.

A single underground repository will accommodate both HLW and TRU wastes. It is assumed that HLW will be stored in air-cooled surface facilities for a period of about 30 years before shipment to the repository site and final disposal. The operating period of the repository is assumed to be about 50-60 years. The total quantity of waste to be disposed of in the repository is calculated to be 400 000 m^3 for TRU waste and 14 000 m^3 for HLW, including certain allowances. The quantity of HLW corresponds to 100 000 tU of spent fuel and 25 700 TWh of the electricity generated from the spent fuel.

2. Geological medium

The site selection process started in the early 1980s with the establishment of a national inventory of potential disposal sites. In view of the broad range of possible host rocks with favourable characteristics, four candidate sites were nominated in 1987. Each of them has a different geological medium; granite, schist, clay and salt. Field investigation started in 1987. The work was suspended in 1990 after drilling on one of the candidate sites. The cost information provided in this Annex is the average of costs of the four candidate sites.

3. Waste management system

3.1. Overview

Long-term industrial management of radioactive waste is carried out by the "Agence Nationale pour la Gestion des Déchets RAdioactifs" (ANDRA), which is responsible for designing, siting, constructing and operating long-term disposal facilities.

In France, radioactive waste is usually classified into two main categories: "short-lived waste" and "long-lived waste", depending on the radioactive half-life of the elements contained in the waste.

Short-lived waste merely contains low- or medium-level beta and gamma elements with a half-life of up to 30 years. Final disposal is carried out in surface repositories. The first near-surface disposal, Centre de la Manche, has been in operation for 20 years. Its total capacity of 535 000 m^3 of waste will be reached in 1994. A second facility, called Centre de Stockage de l'Aube, has a total capacity of 1 million m^3 of waste and started its operation in September 1991. Its annual design capacity is 30 000 m^3 of waste.

Long-lived waste contains significant quantities of alpha emitters. It includes low- and medium-level alpha waste (mainly from spent fuel reprocessing) and HLW (fission products vitrified after reprocessing). For the time being, this waste is stored at production sites. A storage period of approximately 30 years in air-cooled facilities is required for HLW. Then, all waste will be shipped to the deep repository site. The nominal capacity of the repository is assumed to be 400 000 m^3 of alpha waste and 14 000 m^3 of HLW. The opening date of the repository is presently planned between 2010 and 2020 and the operating period will extend over 50 to 60 years (cost information is based on a 50-year operating period).

3.2. Repository surface facilities

All radioactive waste is transported by rail in B-type casks according to the IAEA regulations. On an average daily basis, eight to nine casks are delivered to the site and sorted by waste type upon their arrival at the terminal area of the repository site. The transportation casks are then transferred to the unloading building where the waste containers are unloaded from the transportation casks and stored in interim storage cells. Waste is placed in a shielded transfer cask, and hauled to a surface shaft station and then hoisted down a dedicated waste transfer shaft to an underground station. From 25 to 30 transfer casks will be lowered to the underground facility each day on an eight-hour shift basis.

The surface facilities of the repository include:

- a rail terminal and a reception area;

- an unloading building;
- shaft head frames and hoisting equipment;
- administrative and service buildings;
- workshops, warehouses and garages;
- backfill preparation facility;
- a concrete batch plant;
- power and water supply and distribution;
- exhaust water pond and treatment station;
- waste muck pile.

The total site area is assumed to be approximately 1.5 km². All waste will be prepared at the waste production sites; HLW is vitrified in steel canisters, TRU waste is solidified in concrete or, for sludges, in bitumen, and placed in thin steel or concrete canisters. An encapsulation facility is therefore not considered in the design of french disposal facility.

3.3. Repository underground facilities

As described in Section 2, there are four candidate sites for the repository. Because each candidate site has different host rock and because the design of underground repository strongly depends on the characteristics of the host rock, the repository design of each candidate site is relatively different.

Disposal cavities consist of vertical boreholes drilled down from an upper level (see Figure 1). At this level, the handling drift serves the full row of boreholes. Each borehole will accommodate a single pile of waste packages. Dimensions depend on geology (thickness of the host layer in clay and salt), canister geometry, drilling and handling techniques, mechanical stability and, in the case of HLW, thermal generation: any increase in temperature will be minimised by spacing the HLW disposal boreholes and the handling drifts. Tables 1 and 2 present possible dimensions for the disposal facilities. Maximum heat dissipation in the area for HLW, which depends on the selected host rock, is 15 W/m² on an average.

In hard rock, the "vault" concept (see Figure 2) is envisaged for non-heat-emitting waste, with the lower part of each vault is fitted with a concrete structure divided into vertical pits. The upper part of the vault accommodates the handling equipment used to place the waste packages in the pits.

The handling equipment includes a gantry crane carrying the transfer cask into position over a disposal pit. Each canister is lowered into the borehole and placed on the top of the stack of waste canisters. The annular gap between the wall of the borehole and the canister is filled with mortar or crushed rock. The option consisting of a highly compacted bentonite barrier around HLW canisters in hard rock has not been considered in the cost estimate.

Table 1. **Expected dimensions of TRU waste disposal boreholes**

Type of rock	Hard rock	Clay	Salt
Borehole diameter (m)	1.4-2	1.4-2	1.4-2
Borehole depth (m)	100-110	50-60	65-90
Borehole spacing (m)	7-10	7-10	7-10
Drift spacing (m)	25	25-30	25-30

Table 2. **Expected dimensions of HLW waste disposal boreholes**

Type of rock	Hard rock	Clay	Salt
Borehole depth (m)	100-120	50-60	65-90
Borehole spacing (m)	10-20	10-20	10-20
Drift spacing (m)	80	55-80	80

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Figure 1. **Borehole disposal concept for "C" waste**

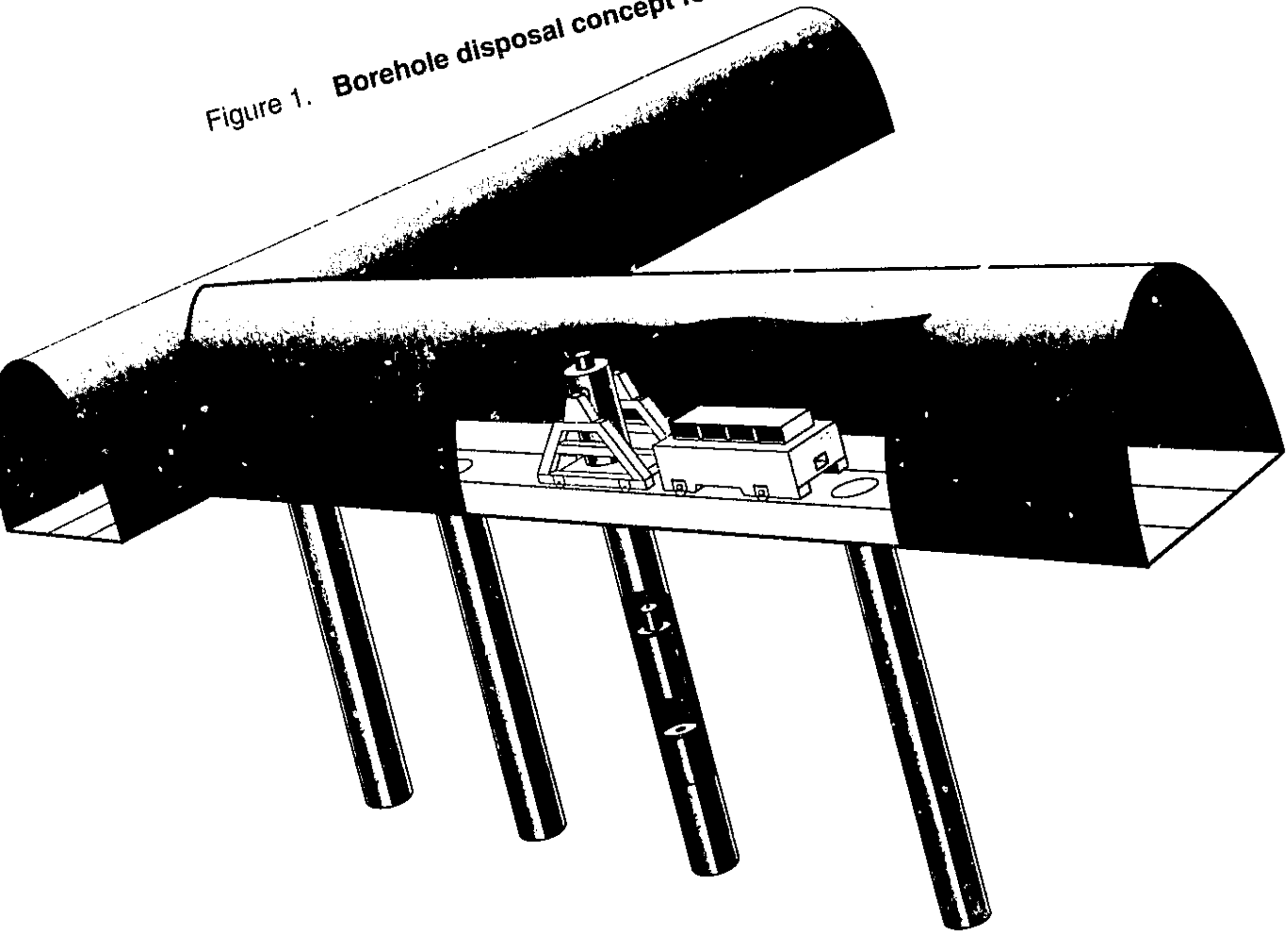
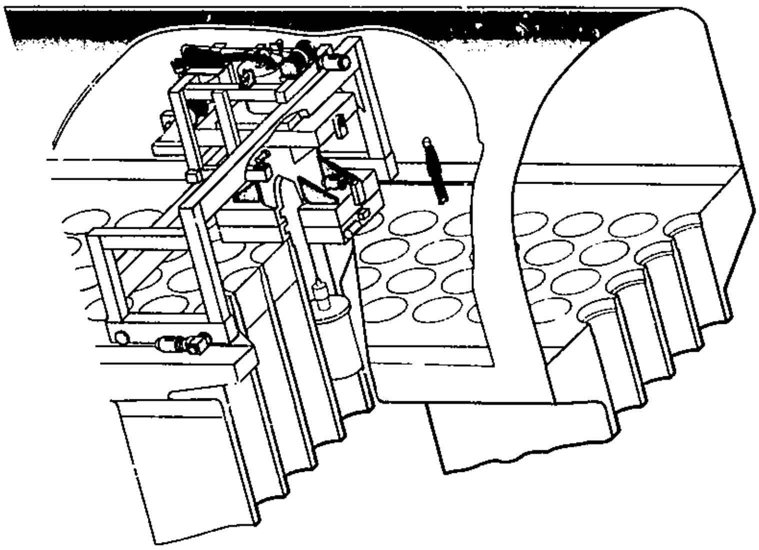


Figure 2. **Vault disposal concept**



Operating equipment is designed to minimise the worker's exposure to radiation. Special care is taken to protect the environment against radiological hazard.

New disposal boreholes and drifts will be constructed progressively during the operation of existing facilities.

The waste disposal area for HLW will be separated from the area for TRU waste. In each area, handling drifts or vaults will be served by several tunnels respectively dedicated to waste haulage, air exhaust, personnel access and construction support.

Other underground facilities include:

- a service shaft used to transport men and material from the surface to the underground facilities;
- a hoisting shaft;
- one or two ventilation raises;
- a central shaft station containing a service area and a crushing unit;
- a waste transfer shaft;
- a waste shaft station with a buffer storage area for transfer casks.

The total area covered by the underground facility ranges from 4 to 10 km^2, depending on the selected geological site. The total volume of excavated rock (including areas for TRU waste and HLW) is estimated to be 4.8 million m^3 on average.

Before decommissioning, all drifts will be backfilled with excavated rock. Closure of the repository includes construction of tight bulkheads in main drifts and access shafts.

3.4. *Time schedule*

The construction of two underground laboratories on two potential sites is planned to start in the early 1990s. Site characterisation studies as well as R&D and on-site experiments, will be carried out during the 1990-2005 time period. Construction of the disposal facility after the one site is selected around the year 2005 will take approximately 10 years. The facility will operate for around 50 years. No costs for surveillance after closure are included in the cost calculations.

4. Results of cost calculations

4.1. *Purpose of the cost calculations*

The cost calculations are performed to provide a basis for defining the financial provisions made by waste producers to cover nuclear back-end activities.

4.2. *General assumptions*

As of September 1991, updated design and operation criteria and corresponding cost estimates are being prepared. Because the revised cost estimates are not yet available, the cost estimates given below are based on a former design and layout. The cost estimates below are from 1989. No costs for surveillance after closure of the repository is considered in the cost calculations. The cost information provided in this Annex is the average of those of the four candidate sites.

The cost calculations were performed on the basis of construction and operation techniques that are available today. The calculations assumed that the today's regulations will be applied.

The costs are given in the price level of 1990. No discounting has been done.

4.3. *Results*

Table 3, combined with the time schedule described in Section 3.4, provides the disposal and encapsulation costs discussed in the main text. It should be noted that some cost items are presented in the form of cost per year or per site. In these cases it is necessary to multiply the cost numbers with a corresponding parameter.

Table 3. **Average cost estimate of French geological disposal**

Cost item	Period	Estimates (M FF)
1. Site characterisation, validation and licensing (1983-2000)		
Preliminary characterisation	1983-1990	1 000
Construction of underground laboratory (for each site)	1992-2000	1 200
Operation of underground laboratory (for each site)	-	800
2. Disposal facility		
Construction		
- Initial investment	-	10 000
- Additional investment (every 5 years)	(9 x)	400
Operation (for each year)	(50 x)	400
Decommissioning and closure	-	1 500

4.4. *Contingencies*

Cost estimates may vary considerably because of the numerous uncertainties that govern the waste management programme. For example the French strategy has changed recently: previously, the site characterisation strategy was to select one site among the four candidates after extensive field work and construct one underground laboratory. The new strategy calls for at least two laboratories. Another uncertainty which has a major impact is the type of rock which will be finally selected: for instance, excavation work is more expensive in clay than in other rocks because of roof support requirements; engineering barriers can be more complex in non-creeping rocks, etc.

The present design of the deep repository is not detailed; finalisation of the design requires a large amount of research work and technological developments. From the experience of other large scale projects, the contingencies are estimated to be 30 per cent.

5. Specific results

In the case of a 50-year operation period, the costs are calculated to be about 37 000 M FF taking into account only one underground laboratory. This corresponds to 370 FF/kgU or 90 000 FF/m^3 of waste or 1.4 M FF/TWh. All these figures are undiscounted.

6. Financing system

In France, radioactive waste producers are responsible for all costs related to waste management. However, the preparation for the future liabilities is left to each waste producer and there is no governmental funding scheme.

References

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HOORELBEKE, J.-M. and J.-M. POTIER (1991), *Design and Operating Criteria of the French Deep Repository for High Level Radioactive Waste*, Proceedings of the Second High Level Radioactive Waste Management International Conference, Las Vegas (USA).

GERMANY

1. General

The German nuclear power programme consists of 23 reactors (7 BWRs and 16 PWRs) with a total net capacity of 23 600 MWe. Approximately 500 tU of spent fuel is annually discharged from these reactors. According to the Nuclear Energy Act, reprocessing and recycling of uranium and plutonium has the first priority for the treatment of spent fuel. But an adaptation of the legal basis is under discussion to make direct disposal available as an alternative.

In a reference scenario used for a cost analysis of geological disposal in 1986, it was assumed that 700 tU of spent fuel (corresponding to 26 GWe electricity generation capacity) should be annually managed by reprocessing (500 tU of 700 tU) and by direct disposal (200 tU of 700 tU) over the repository operation time of 50 years. In the case of spent fuel, emplacement in the repository could be performed after an interim storage period of 30 years (10 years in reactor pools and 20 years in an interim dry storage facility) and 40 years in the case of high-level vitrified waste (HLW). In addition, HTR (high-temperature reactor) fuel (1 million elements per year; 11.3 tHM per year; corresponding to 1.2 GWe electricity generation capacity) and heat generating (alpha-bearing) intermediate-level wastes from reprocessing plants will be disposed of in the same repository. HTR fuel will be emplaced in the repository immediately after reactor discharge.

The total quantity of waste considered for disposal in the repository is 10 000 tU of spent fuel, 25 000 tU of HLW, 565 tHM of HTR fuel and 48 100 m^3 of alpha-bearing waste. The corresponding total electricity production in the nuclear power plants will be 8 340 TWh [27.2 GWe x 50 years x 365 x 24 x 0.7 (load factor)]. Although the waste volume (including canisters and overpacks) is affected by several technical boundary conditions, the volume is tentatively estimated to be 95 800 m^3 (spent fuel: 26 000 m^3, HTR spent fuel: 17 500 m^3, HLW: 4 200 m^3, alpha-bearing waste: 48 100 m^3).

The repository will be built at about 870 m depth in the Gorleben salt dome, if it proves suitable. In the reference concept, the spent fuel will be packaged at the repository site into POLLUX casks, which consist of an inner repository canister and the outer shielding overpack. Vitrified HLW, which is solidified in steel canisters at reprocessing plants, will be emplaced in deep boreholes underground. HTR fuel is repacked in the conditioning plant into 400-L drums and then emplaced in the same type of boreholes as the HLW.

2. Geological medium

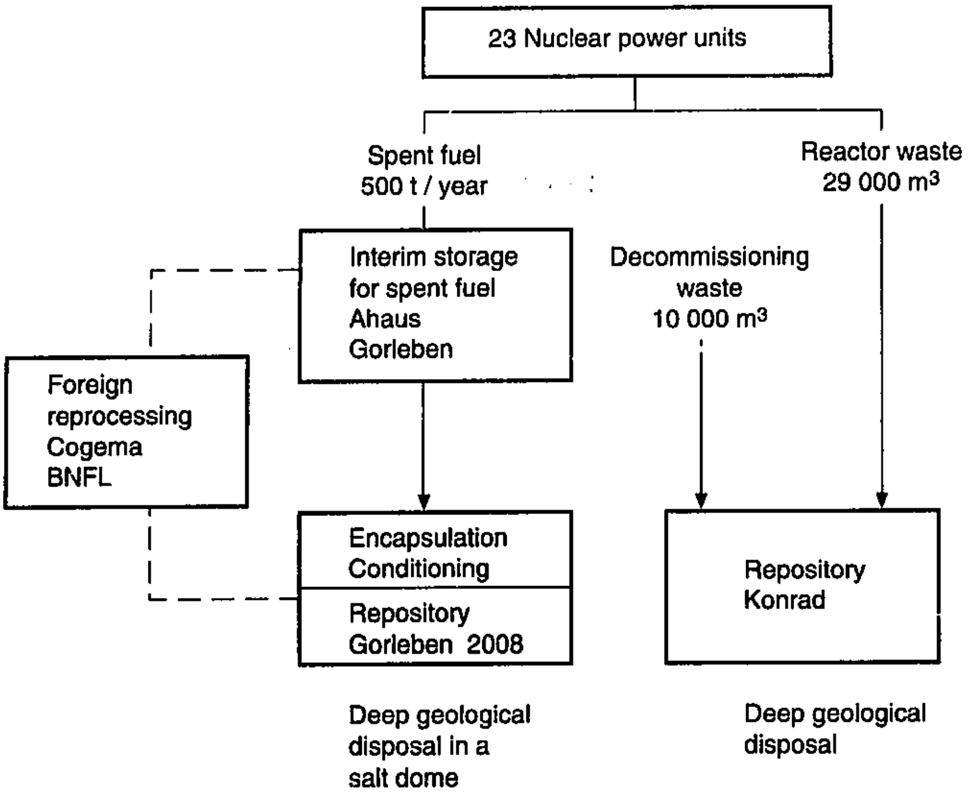
The repository for heat-generating waste (including spent nuclear fuel) is planned to be built in the Gorleben salt dome, which has been under investigation for its suitability since about 10 years ago. The design of the repository will ensure that the temperature will not exceed 200°C at the surface of any canister or overpack.

3. Waste management system

3.1. Overview

The German radioactive waste management system is shown schematically in Figure 1. This figure corresponds to the actual situation in Germany, not to the basis of the cost analysis. Low- and intermediate-level short-lived waste is planned to be disposed of directly in an underground repository at Konrad.

Figure 1. **Main system for management of radioactive waste in Germany**



The spent nuclear fuel is transported, after about 10 years of storage in the reactor pools, either to foreign reprocessing facilities or to interim storage facilities by truck. For the transportation and interim storage of spent fuel, CASTOR and TN casks have been developed, both of which can handle about 10 t of spent fuel per cask. The interim storage facilities are located at Ahaus and Gorleben, and each facility can accommodate 420 casks and 1 500 t of spent fuel.

Spent fuel will be stored for about 30 years to allow for the residual power to decay to a level which is suitable for disposal to the repository. The fuel is then transported to a conditioning facility which is assumed to be collocated with the final repository. The cost calculation described in Section 4 includes the costs of the conditioning facility.

HLW is vitrified in steel canisters at reprocessing plants. The HLW is assumed to be directly transported to the repository site after a cooling period of 40 years. No special conditioning for disposal is considered for HLW.

HTR fuel is assumed to be repacked into 400-L drums in a conditioning facility outside the repository site. Although an annual amount of 1 000 000 HTR spent fuel elements is assumed in the cost calculation, HTR fuel is neglected in Figure 1, since there is no HTR in operation or planned for the next few decades.

3.2. Site services

At the repository site, the conditioning facility is built directly above the repository. In addition to this there are personnel facilities including housing, goods reception station, workshops, vehicle service. A water supply and sewage system is also included. The total site area is approximately 0.8 km^2.

3.3. Conditioning facility

A conditioning facility will be collocated with the repository. In the facility the spent fuel will be emplaced into POLLUX repository casks. HLW fuel will be conditioned at the production sites, not at the repository site. The capacity of the facility is assumed to be 250 to 350 tU of spent fuel per year. The conditioning facility will be designed on the basis of the technique used in a pilot conditioning plant that is described below.

The pilot conditioning plant is currently under construction at the interim storage site in Gorleben. The pilot plant is designed to accept a maximum of 35 tU of spent fuel annually for encapsulation into POLLUX-type repository casks.

The spent fuel will be transported to the pilot plant in special shipping casks, and then unloaded from the casks in a conditioning building. The unloaded fuel elements will be disassembled mechanically into fuel rods and structural parts. In order to save space, the fuel rods will be packaged in bins while the structural parts will be packed in baskets. Each repository cask, which is designed to withstand the mechanical stress due to the rock pressure, can accommodate four bins and one basket.

The inner repository canister of the POLLUX cask is a cylinder about 5.0 m long and 1.0 m in diameter with a wall thickness of 150 mm. Depending on the specific POLLUX type, one cask accommodates up to 24 BWR or 8 PWR fuel elements, or about 4 t of uranium. The actual number of fuel elements per cask is determined by the residual power of the fuel elements. The total power of a cask at disposal shall not exceed 6-7 kW. A first lid is bolted in place, then a second lid is inserted and welded. In addition, the inner repository canister is placed in an outer shielding overpack, into which another lid is screwed. This completes the POLLUX cask for final disposal.

The operating staff of the pilot conditioning plant is expected to be about 50 employees. It should be noted that the cost calculation described in Section 4 does not include the costs of the pilot conditioning plant, but the costs of a later 250-350 t conditioning plant.

3.4. Repository

The repository is planned to be built at a depth of about 870 m (emplacement level) using the underground exploration level at a depth of 840 m for air exhaust. Two shafts are required for the mining and emplacement activities. The repository consists of a central infrastructure section and the emplacement section which are located between two parallel access drifts connected by cross-cuts.

Canisters (filled with HLW from the reprocessing) and drums (filled with HTR fuel elements), which do not have special shielding, are assumed to be emplaced in boreholes 300-600 m deep vertically drilled in the bottom of drifts. Shielded casks of the POLLUX type, which contain spent fuel, are assumed to be emplaced in drifts. A schematic layout of the repository is shown in Figure 2. The distances between the emplacement boreholes and between the drifts are determined by the limitation of the maximum allowed temperature and further requirements still to be quantified by performance assessments. In a design assumed in the cost estimate, the allowed temperature at the surface of the canister or cask is 200°C and the resulting maximum heat load of the repository is 33 207 kW (324 kW/ha).

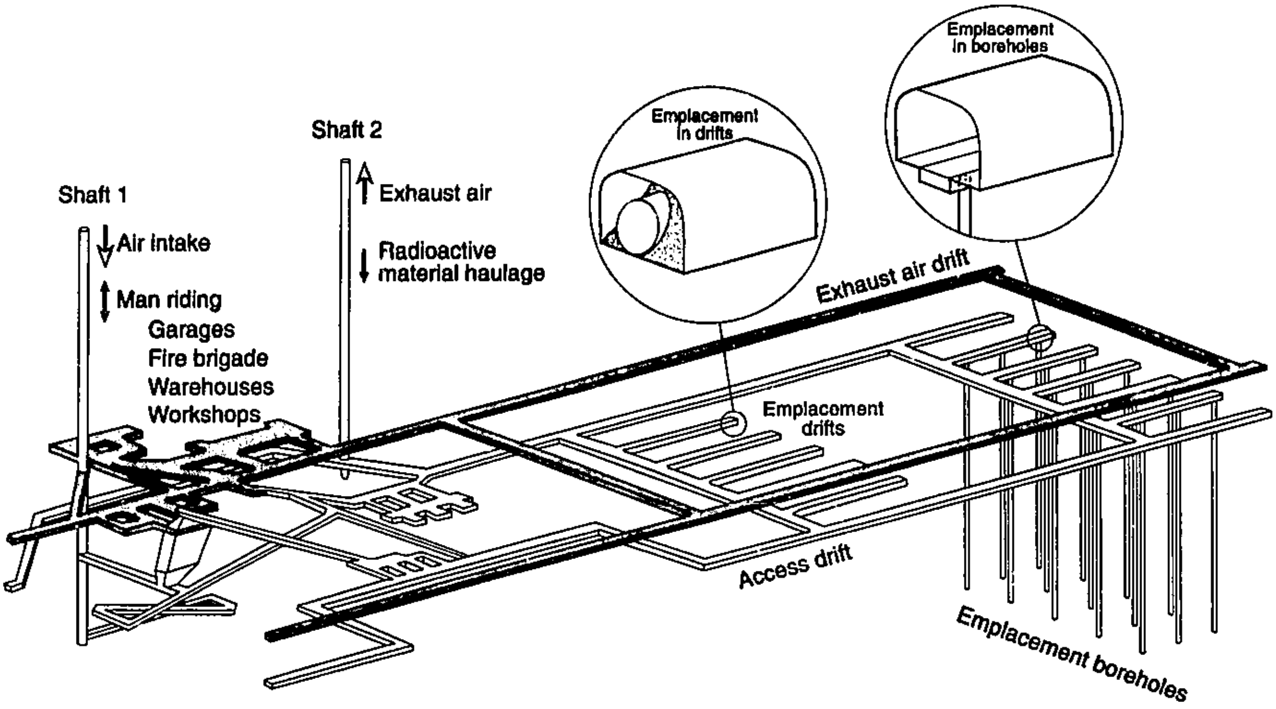
The emplacement drifts will be excavated as the waste is emplaced. The drifts and emplacement boreholes will be backfilled with crushed salt from the excavation shortly after the emplacement of each waste package. The emplacement, backfilling and sealing activities can always be physically separated from the excavation activities.

For drilling and tunneling, conventional techniques will be applied. In cross section, the access drifts will be about 28 m^2 and the emplacement drifts about 14 m^2. The total excavated rock volume depends strongly on the future evolution of waste management concept and waste arisings, but it is currently estimated to be 2.5 million m^3.

The POLLUX-type casks and transfer casks (for canisters and drums) are planned to be transported by rail car. Special equipment will be used to emplace the POLLUX casks in drifts, and the canisters and drums in boreholes.

Operations will employ about 260 persons, including teams for emplacement, mining and backfilling activities.

Figure 2. **Schematic layout of a repository for borehole and drift emplacement**



3.5. Time schedule

The Gorleben salt dome is being investigated for its suitability as a host rock of a repository. Site investigation and characterisation should be completed by 1997. Due to licensing and construction, the waste will not begin to be emplaced until 2008. Depending on the suitable volume of the salt dome, an operation time of 50-70 years is assumed before sealing and decommissioning. In the cost calculations, no costs for surveillance after closure are included.

4. Results of cost calculations

4.1. Purpose of the cost calculations

The costs were calculated as part of an R&D project for the direct disposal of spent fuel in order to determine the most economical solution considering several alternatives regarding:

- different ratios of fuel to be reprocessed and of fuel to be disposed directly;
- different periods of interim storage (cooling time of spent fuel after discharge from reactors);
- different conceptual designs for the repository.

The analysis did not consider the costs for transport outside the repository site and costs for reprocessing, because these do not affect the costs for disposal concepts.

This Annex provides the results of one of the cost calculations.

4.2. *General assumptions*

The cost calculations are performed at the 1988 price level. The techniques applied for construction and operation are those generally available today. It is also assumed that today's codes and regulations will be applied to the construction and operation of repository. The costs were not discounted.

4.3. *Results*

In Table 1, the results are presented separately for the conditioning and the repository, and divided among the following cost categories: investment, operation, casks, and taxes and insurance. The cost item "investment" includes the costs for site evaluation, stand-by during the licensing procedure, construction of the repository, reinvestment and dam construction.

Table 1. **Results of cost calculation**

Million Deutschemark, Price level 1988[a]

Cost item	Conditioning	Repository
Investment	650	2 559
Operation	775	2 229
Casks	1 645	–
Taxes and Insurance	423	–
Reinvestment	–	697
Total	3 493	5 485

a) No discounting has been done.

According to the cost calculations made for different repository concepts and different cooling periods of the spent fuel, the cost estimates range from 2 per cent for "investment" and 12 per cent for "operation". About 80 per cent of the total investment is independent of repository concepts.

4.4. *Contingencies*

The purpose of this analysis is to determine the most economical solution among several alternative scenarios and conceptual designs for the repository. Therefore, contingencies of up to 50 per cent were made for uncertainties in the project definitions.

5. Specific results

The total cost given above is DM 8978 M. Corresponding specific results are thus 256 DM/kgU or 1 077 M DM/TWh. The cost figure of 8 978 M DM includes the costs for repository site evaluation of about 1 500 M DM. This cost item is excluded from the cost figure used in the international comparison in the main text.

6. Financing system

According to the German legislation, the costs for final disposal of radioactive waste shall be borne by companies that handle certain amounts of radioactive materials. Costs are annually specified by the Bundesamt für Strahlenschutz (BfS) for site-specific R&D, projects in Gorleben, projects in Konrad, etc. A distribution key is applied to determine the corresponding fees to be paid by waste-producing companies to BfS. The nuclear power plant owners are charged 17.5 per cent directly and indirectly (*i.e.*, for reprocessing) plus an additional 75 per cent of the total annual costs. The residual 7.5 per cent is charged to other waste producers. The total costs for final disposal for the time period of 1977 to 1988 will accumulate to 1 078 million DM.

Reference

Kernforschungszentrum Karlsruhe GmbH, *Systemanalyse Mischkonzept*, Karlsruhe, December 1989.

BRENNECKE P. and J. SCHUHMACHER, *Radioaktive Abfälle in der Bundesrepublik Deutschland - Bestand, Anfall, Zwischen- und Endlagerung*, Atomwirtschsft, November 1990.

NETHERLANDS

1. General

The nuclear power programme of the Netherlands consists of two reactors (one BWR and one PWR) with a total net capacity of 508 MWe. The reactors have been commissioned in 1969 and 1973. In the cost calculations, some cases for the future development of the nuclear programme are assumed (see below).

The strategy adopted for the management of the spent nuclear fuel is a reprocessing scenario. However, as yet no decisions have been taken with respect to the final disposal of radioactive waste. Disposal into a deep geological repository in the Netherlands is studied as an option. A safety and feasibility study of geological disposal is under way and it will continue at least until the middle of the 1990s. Neither site selection into a research specific site has begun; a separate decision will be made by the government and the parliament.

In one of the studies in this programme, cost estimates for two disposal concepts, taking account of three disposal strategies for the Netherlands are under consideration. The three disposal strategies are described in detail under Section 3.1. For some waste, production scenarios have been prepared. This cost calculation study, which yielded rather global results, dates back to the mid-1980s. In all cost calculations, it is assumed that all radioactive waste (not only vitrified high-level waste but also intermediate- and low-level active waste including the radioactive waste produced by hospitals and research laboratories) produced in the Netherlands will be disposed in a repository.

2. Geological medium

The radioactive waste repository is planned to be built in a salt rock formation in the Netherlands. The feasibility studies yielded a number of salt formations eligible for further investigation. No specific site was chosen for the cost calculation; the study is therefore site-independent and provides global results.

The feasibility study considered the three salt rock formations:

- salt dome: depth of 300-3300 m, disposal between 600 and 1500 m (maximum);
- salt pillow: depth of 450-800 m, disposal between 550 and 700 m;
- bedded salt structure: depth of 1 200-1 600 m, disposal between 1 300 and 1 500 m.

Cost calculations were performed for these formations.

These salt formations offer sufficient space for disposal and lie at such a "shallow" depth that mining engineering activities can be performed. Underground salt mining has been practised for ages. The known techniques have potential applications for the disposal of radioactive waste in rock salt.

3. Waste management system

3.1. *Overview*

The Netherlands has adopted the reprocessing option as the strategy of spent fuel management for existing nuclear power plants. In the cost calculations, this strategy is supposed to be applicable to expansion scenarios. Resultant high-level vitrified waste will be disposed after a certain period of interim storage. A facility for long-term interim storage (50-100 years) is currently under construction near the Borssele power plant. This facility can accommodate all radioactive waste produced in the Netherlands for the coming decades (50-100 years). All handling of the waste, which is necessary for storage and disposal, is dealt with at the interim storage facility. The costs for construction and operation of this interim storage facility are not included in the scope of the cost calculations described in Section 4. The Central Organisation for Radioactive Waste Management (COVRA) is responsible for the storage and disposal of all radioactive waste in the Netherlands.

The cost calculations described in Section 4 assume three disposal scenarios:

i) Scenario A: Only existing nuclear power plants; 50 years interim storage of high-level vitrified waste; final disposal in 2050-2060. The amount of radioactive waste to be stored is based on:
  - 70 years (1985-2055) waste supply from hospitals and research laboratories;
  - 20 years (1985-2005) waste supply related to the operation of the nuclear power plants at Borssele and Dodewaard;
  - reprocessing of all the spent fuel from the plants at Borssele and Dodewaard.

ii) Scenario B: Existing nuclear power plants plus 3 GWe new nuclear capacity; 50 years interim storage of high-level vitrified waste; final disposal in 2080-2095. The amount of radioactive waste to be stored is based on:
  - 105 years (1985-2090) waste supply from hospitals and research laboratories;
  - 20 years (1985-2005) waste supply related to the operation of the nuclear power plants at Borssele and Dodewaard;
  - 30 years (2000-2030) waste supply related to the operation of the nuclear power plants related to 3 GWe extra capacity;
  - reprocessing of all the spent fuel from the plants at Borssele and Dodewaard and the extra 3 GWe nuclear capacity.

iii) Scenario C: Existing nuclear power plants plus 3 GWe new nuclear capacity; limited (10 years at most) interim storage of high-level vitrified waste; final disposal in 2010-2045. The amount of radioactive waste to be stored is based on:
  - 55 years (1985-2040) waste supply from hospitals and research laboratories;
  - 20 years (1985-2005) waste supply related to the operation of the nuclear power plants at Borssele and Dodewaard;
  - 30 years (2000-2030) waste supply related to the operation of the nuclear power plants related to 3 GWe extra capacity;
  - reprocessing of all the spent fuel from the plants at Borssele and Dodewaard and the extra 3 GWe nuclear capacity.

iv) Scenario C': The same as "scenario C"; but with a demonstration facility for high-level vitrified waste and an earlier start of low- and intermediate-level waste disposal.

In all scenarios, the operating life of the nuclear power plants is assumed to be 30 years. It is assumed that the reprocessing wastes need no further complex conditioning at the disposal site. In the case of scenario B, the total amount of spent fuel discharged from reactor is estimated to be 2 012 tU and the corresponding electricity generation is 631 TWh.

Resultant estimates of the waste amounts to be disposed of in the repository are: 53 810 m^3 for scenario A, 139 189 m^3 for scenario B, 123 693 m^3 for scenario C and C'.

3.2. *Site services*

The high-level vitrified waste is transported from the interim storage facility to the disposal site in special transport casks. At the disposal site, the waste is removed from the transport casks and temporarily put into vaults. Further transport (*e.g.*, to an underground repository) will be carried out with special disposal site casks. The disposal site contains facilities for the remaining handling of the waste, for short time storage, decontamination services, salt storage, salt mills, etc. In addition, there are personnel facilities, a water supply and sewage system, etc. The site comprises about 40 ha. The operating staff for the site services is estimated at about 150 persons.

The costs for site services are included in the scope of the cost calculations but the costs for the transportation from the interim storage facility to the disposal facility are not included in the calculation. Any special improvements of infrastructure such as roads and ports are not considered in the cost calculations.

3.3. Encapsulation facility

All handling of the waste, which is necessary for storage and disposal, is dealt with at the reprocessing facility or the interim storage facility. Therefore an encapsulation facility is not considered in the disposal plan.

3.4. Repository

The feasibility studies focuses on two disposal concepts:

- A conventional mine with shafts and galleries. At the gallery level, spaces are constructed for non-heat-producing waste; the high-level heat-producing (thermogenic) waste is disposed of in deep boreholes extending several hundred meters downwards from the floor of the galleries.
- Boreholes drilled from the surface for the disposal of high-level heat-producing waste, in combination with different types of caverns for non-thermogenic waste. The operation of the caverns can be wet or dry; both concepts have advantages and disadvantages.

The vitrified waste and high-level waste packages are 1.3 to 1.7 m long with a diameter of 0.4 to 1.25 m. The weight ranges from 0.5 to 4.0 tonnes per package. The total heat production of a vitrified waste package will not exceed 400 W. The minimal disposal distances for the packages in deep boreholes is 100 m, in caverns 150 m (in the borehole and cavern concept). The borehole distance in the galleries for the mine concept is 50 m. These distances are determined by the limitation of the maximum allowed temperature, which is 150°C (max.) and by the rock conditions. The maximum allowed temperature in and around the repository is assumed to be 100°C. The resulting design-base heat load of the repository is 824 kW. However it should be noted that this figure represents the calculated heat load. The maximum heat capacity of the whole repository is much higher. Furthermore, it should be noted that differences in borehole depth, nature and heat conductivity between the host rocks under consideration limit the validity of any comparison of this figure to other repository concepts (*e.g.*, granite).

The depth of the repository depends on the type of geological medium described in Section 2. Boreholes as well as the shafts of mines and caverns will be drilled. The mines and caverns will be excavated with brine solution. The volume of the excavated salt rock for a mine in strategy C' comprises about 1.25 million tonnes, of which 0.5 million tonnes can be reused as backfill after the waste is deposited. For sealing, other material such as cement, bitumen, etc., will be used.

About 75 to 125 people will be working during the construction of the boreholes, caverns and mine.

3.5. Time schedule

The timing of waste disposal for each disposal scenario is described in Section 3.1. It is estimated that construction and other activities will start about five years before the final disposal begins in the case of the borehole and cavern concept. For the total mine concept in strategy B, nine years will be necessary, whereas for the other strategies six to seven years will be necessary. Five years will be needed for closure and decommissioning in both concepts. No long-term monitoring is planned after closure and decommissioning.

4. Results of cost calculations

4.1. Purpose of the cost calculations

The cost calculations described below are performed in the feasibility studies for geological disposal. Because the purpose of the study is not to provide a basis for determining an adequate fee to be levied on nuclear power production to finance back-end activities, the cost calculations are made in a way of the best estimation. To take account of uncertainties in the estimate, an allowance of 15 per cent is applied for contingencies.

4.2. *General assumptions*

The costs directly related to the final disposal have been estimated for different scenarios, for different salt rock formations and for different disposal concepts. It should be noted that those estimates do not include reprocessing or other waste treatment costs. Nor are costs for interim storage or transport outside the repository site included.

Other important assumptions are:

- the cost calculations are performed in the price level of the end of 1985. No discounting was done;
- the techniques applied for construction and operation are assumed to be those that are generally available today;
- the codes and regulations of today are applicable;
- costs for R&D, site acquisition and infrastructure improvement outside the site are not included;
- encapsulation for disposal at the disposal site is not considered in the disposal scenarios;
- no costs related to storage and disposal of excavated salt rock are included;
- there is no allowance for retrievability and long-term monitoring.

4.3. *Results*

In Table 1, the results are presented for the combinations of disposal scenario, disposal concept and geological medium. It should be noted that no decision in favour of any concept, scenario or geological medium has been taken in the Netherlands. The cost estimates in Table 1 comprise the costs for site selection; licensing, design, construction and operation of disposal facilities; supply of electricity and water; transport and communication; machines; and sealing, closure and decommissioning of the facilities. An allowance of 15 per cent is made for contingencies.

Table 1. **Summary of cost results for different disposal facilities**

M fl., price level of the end of 1985[a]

Concepts	Deep boreholes and caverns (dry)		Deep boreholes and caverns (wet)			Mine	
Medium	Dome	Pillow	Dome	Pillow	Bedded salt dome	Dome	Pillow
Scenario A	240.6	356.2	290.8	406.5	543.2	454.8	484.7
Scenario B	626.8	1 198.7	729.8	1 309.9	2 030.5	855.1	901.1
Scenario C	1 016.8	1 578.7	1 092.9	1 654.7	2 329.9	–	–
Scenario C'	–	–	–	–	–	1 648.6	1 684.6

a) No discounting has been done.

For the cost estimates in Table 1, operational costs range from 25 to 70 per cent of total costs. Total costs in scenario C/C' are considerably higher than those in scenario B, because of the higher personnel costs in scenario C/C'.

For the cost comparison in the main text, the cost estimate for scenario B is used. Within this scenario, the salt dome mine concept is considered because this scenario is comparable those chosen by other countries. This choice does not prejudge future decisions in the Netherlands but is exclusively made for reasons of comparison in the main report. The variability of the cost estimates in the table is treated in Chapter 7. In scenario B, the costs related to the salt dome mine concept are 855.1 million florins. This cost estimate does not include the costs for site selection.

5. Specific results

In the reference case, the cost estimate used in the main text is 855.1 M f. This corresponds to 428 f/kgU or 6 100 f/m^3 of waste (including package) or 1.35 M f/TWh of electricity generated. All these figures are undiscounted.

6. Financing system

As was indicated in Section 3.1, COVRA is responsible for the storage and disposal of all radioactive wastes in the Netherlands. COVRA is obliged to negotiate the costs of waste disposal with the waste producers. Waste producers will pay a tariff to the COVRA for the disposal when the COVRA receives the waste. If it turns out that the collected money for a waste category is not sufficient for the disposal of those wastes, the shortage will be compensated by increasing the price of the future waste in that category.

COVRA has not yet determined a tariff for vitrified waste and high-level waste. For the time being, it is therefore up to waste producers to make their own financial provisions. In the near future, COVRA will decide the tariff and begin to set up a fund for the final disposal of high-level wastes.

As long as no decisions on final disposal are taken in the Netherlands, the "best cost estimates" will be used for determining an appropriate amount of the fund and tariffs. Each year, the adequacy of the amount of the fund will be reviewed. If, at a certain time, a larger fund is deemed necessary, the costs will have to be borne by the wastes produced from that time onwards.

Reference

VAN HATTUM EN BLANKEVOORT (1986), *Site-independent study concerning construction, operation and closure of possible facilities for final disposal of radioactive waste in salt rock formations in the Netherlands*, Beverwijk.

SPAIN

1. General

The Spanish nuclear power system has nine LWR reactors (seven PWR and two BWR) with a total net capacity of 7 034 MWe. A GCR reactor (490 MWe) was phased out in August 1990 after 18 years of commercial operation. The first two reactors (PWR - 152 MWe, BWR - 435 MWe) were commissioned in 1969 and 1971, respectively, the rest during the period from 1981 to 1988.

The strategy adopted for the management of the spent fuel is the open cycle, where the spent fuel is considered as a waste to be disposed of in an underground repository.

At the end of 1990, some 970 M tU of spent fuel were stored in the reactor pools (640 – PWR, 330 – BWR). Considering a 30-year operational lifetime for nuclear power plants (NPP), the foreseen total amount of spent fuel to be managed in Spain will be about 5 300 M tU (4100 – PWR, 1200 – BWR), which can be equated to a production of some 1 420 TWh.

2. Waste management milestones

Royal Decree 1522/1984 authorised the constitution of ENRESA (Empresa Nacional de Residuos Radiactivos, S.A.) stipulating, among other tasks, that ENRESA shall be responsible for the siting, design, construction and operation of a repository for the disposal of HLW.

Since 1986, ENRESA has been carrying out a series of studies seeking the best possible solution for the interim storage of spent fuel. Whatever the option chosen, the design capacity of the facility should be enough to hold all the Spanish spent fuel production, so that it can be safely stored, before disposal, for a minimum cooling period of 30 years.

In 1986, a site selection programme was initiated, with a National Inventory of Favourable Formations, considering granite, salt and clay as potential host media. The programme has been progressing since, with studies at different scales; at present 37 areas, selected as favourable on previous work, are being studied. This process will conclude, at the end of the century, with the designation of potential sites for further characterisation.

In 1988, ENRESA initiated the process for the design, licensing and manufacture of dual-purpose metal casks, to be used either in an away-from-reactor (AFR) or an at-reactor (AR) storage facility.

The preliminary non-site-specific design, at a conceptual level of two repositories, one for granite and one for salt, started in 1990. The purpose of this effort is to select a reference concept for the safe disposal of spent fuel, according to national and international standards, with the available technology and at an affordable cost.

3. Cost calculations

The conceptual design, thus far, has produced a cost evaluation for each of the alternatives selected. Therefore, in the following paragraphs, the cost affecting parameters are tabulated for definition purposes.

3.1. Waste characteristics

For the conceptual design, a round number of 14 600 PWR reference fuel elements, whose characteristics are described below, have been considered. The figure came from adding the foreseen production of PWR and BWR fuel elements, plus a safety margin of 25 per cent, assuming that three BWR fuel assemblies correspond to one PWR fuel assembly.

Fuel element, type	PWR 17 x 17 W. st.
Burnup	40 GWd/tU
Initial U_{235} enrichment	4.1%
Initial heavy metal weight	461.4 kg
Heat output per tU (30 years)	860 W

3.2. Repository time schedule and scope

The construction of the disposal facility is planned to start in 2016. The design considers an operational life of 25 years beginning in 2026.

The concepts consider the conditioning plant to be located at the site. Figures 1 and 2 are an artist's view of the surface and underground facilities, respectively, for the salt option.

3.3. Waste conditioning

The concept considers the conditioning of intact spent fuel in containers with the following characteristics:

	Granite	*Salt*
Self-shielded	No	Yes
Canister material	Steel	Steel
Outer shield	–	Cast carbon steel
Length (m)	4.5	5.5
Diameter (m)	0.8	1.6
Internal filling	Glass beads	No filling
Canister capacity	3 PWR	4 PWR
Weight with fuel (t)	13	65

3.4. Disposal concept

The disposal mode developed for both host rock types is drift disposal in parallel galleries excavated in a mined repository with the following main characteristics:

	Granite	*Salt*
Depth (m)	500	800
Access	Ramp	Shaft
N° of shafts	3	2
Thermal density (kW/ha)	52	96
Buffer material	Compacted bentonite	Excavated rock
Backfill material	Sand/bentonite	Salt concrete

Figures 1 and 2. **Artist's view of surface and underground facilities (salt)**

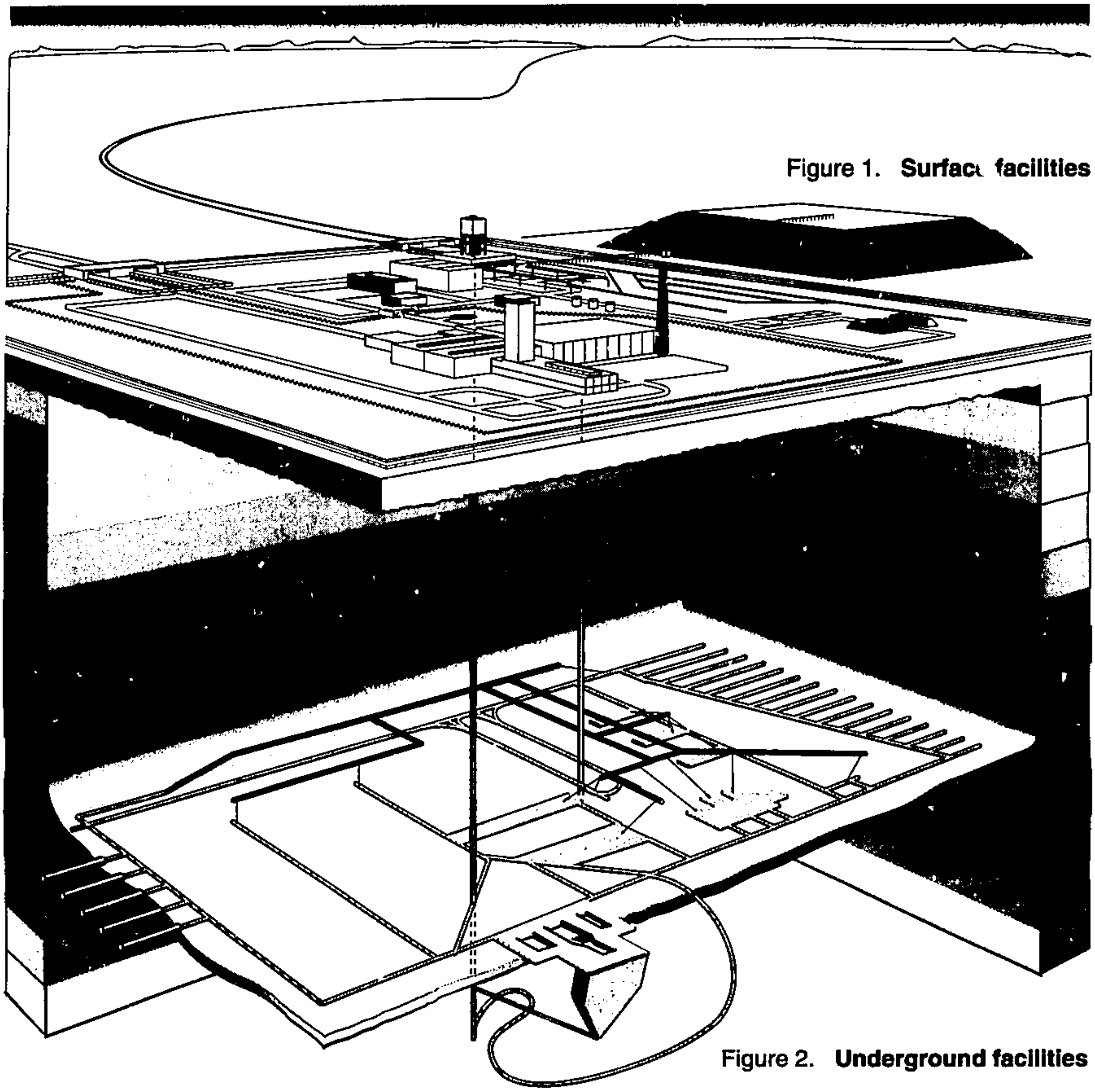


Figure 1. **Surface facilities**

Figure 2. **Underground facilities**

4. Results of cost calculation

The cost information given below corresponds to the cost scope recommended in Table 4.1 of the main text. In the Spanish study, costs for R&D and siting (including characterisation of candidate sites) are estimated to be 45 billion pesetas and 65 billion pesetas respectively for both host rocks. The cost is given in billion January 1991 Spanish pesetas (BPT 91). No discounting has been considered.

The costs for each option correspond to 6 740 tU of spent fuel, equivalent to a production of some 1 900 TWh of electricity. As this waste amount is estimated assuming a 40-year operating period for the nuclear power plants, it is different from the numbers described in Section 1 above.

The total cost for the granite option is estimated at some 220 BPT 91; this figure is broken down as follows:

	Surface facilities	*Underground facilities*
Investment	60	34
Operation	63	17
Sealing	–	40
Decommissioning	5	1
TOTAL	128	92

The total cost for the salt option is estimated at some 260 BPT 91, which can be broken down as follows:

	Surface facilities	*Underground facilities*
Investment	43	37
Operation	146	24
Sealing	–	8
Decommissioning	2	0
TOTAL	191	69

The excavation cost of depositional galleries is included as investment and the cost of the containers as operation.

5. Specific results

Concept	*Unit*	*Granite*	*Salt*
Canister	Number	4 870	3 650
Amount of waste (spent fuel)	tU	6 740	6 740
Waste volume	1 000 m^3	11	40
Corresponding electricity generation	TWh	1 900	1 900
Excavated rock volume	1 000 m^3	600	1 300
Unit cost per tU	MPT 91/tU	33	39
Unit cost per m^3 of waste	MPT 91/m^3	20	7
Unit cost per TWh	MPT 91/TWh	116	137
Unit cost per m^3 of rock	KPT 91/m^3	153	53

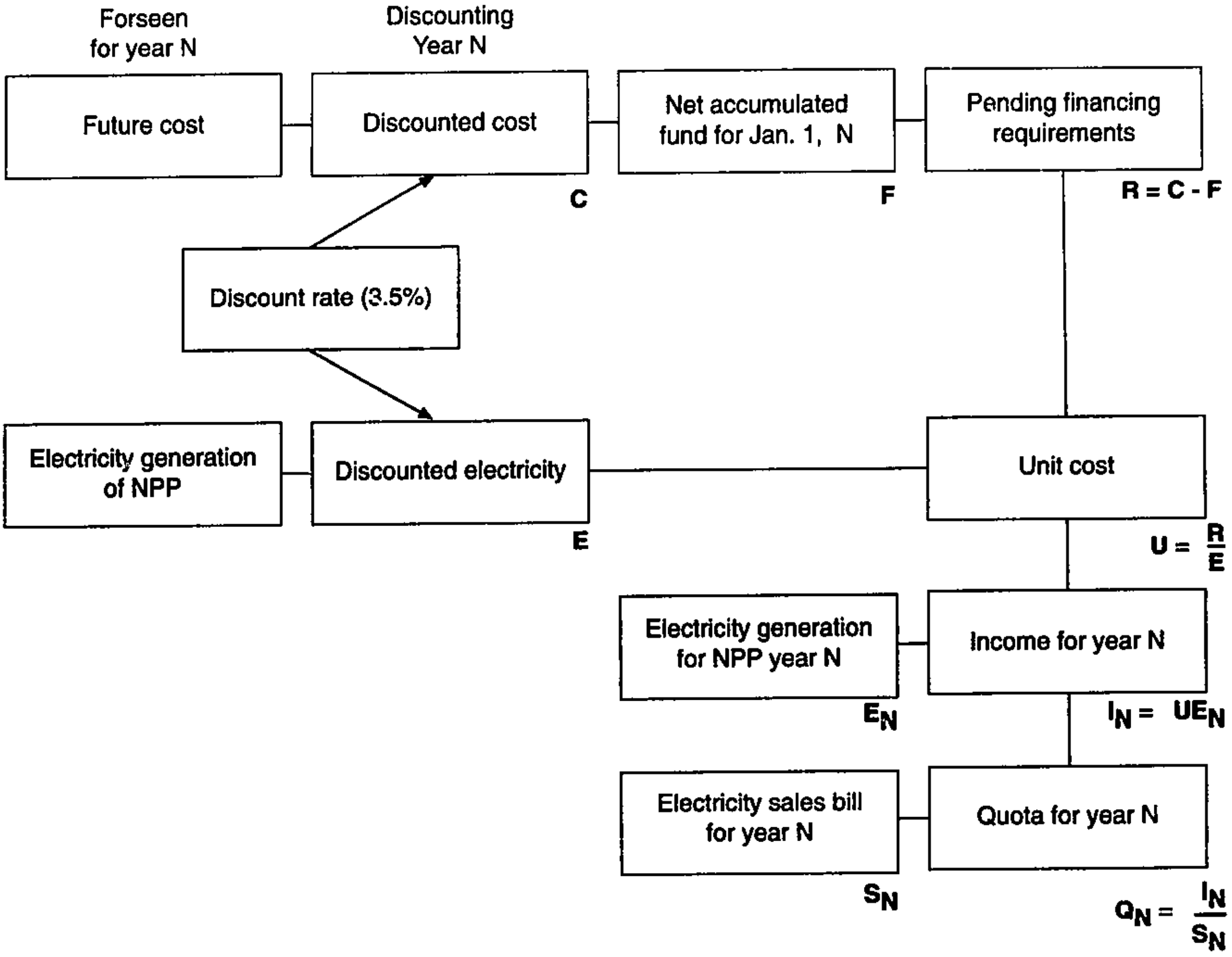
6. Financing system

In order to finance the costs to be incurred in the future, a system of payment on account has been established. The approach adopted for funding back-end activities is to levy a certain percentage (referred to as a "quota") on electricity sales. The incomes resulting from the quota, when added to the accumulating interest on the fund, will meet the projected future expenditures for the complete nuclear waste management (including LLW transportation and disposal, spent fuel and HLW transporation, storage and disposal, NPP decommissioning, GCR fuel reprocessing, R&D and overheads).

An assessment of the future cost for complete waste management has been made. This estimate is revised annually and included in the PGRR submitted to the government for approval.

The methodology for calculating the quota is based on the principle that one year's income will be proportional to the electricity generated by NPPs during that year. Figure 3 shows the steps followed in the calculation. The reference value for the discount rate is 3.5 per cent. Sensitivity analysis was also performed for discount rates of 2 and 5 per cent.

Figure 3. **Calculation of the quota for year N**



The Royal Decree authorising the annual revision of the electricity rates, establishes the value of the quota according to the estimation made in the PGRR. The value of the quota currently in force (1992) is 1.2 per cent, of which about 35 per cent corresponds to final disposal of HLW. The present fund (January 1992) is about 100 BPT.

SWEDEN

1. General

The Swedish nuclear power programme consists of twelve reactors (nine BWRs and three PWRs) with a total net capacity of 9 970 MWe. The reactors were commissioned in the period 1972 to 1985. In the cost calculations, it is assumed that all the reactors will be in operation until 2010, which means that the operating life of the reactors will be 30 years on an average. The corresponding total electricity production in the nuclear power plants will be 2 000 TWh.

The strategy adopted for the management of the spent nuclear fuel is direct disposal after about 40 years of interim storage. Only 140 tonnes of fuel will be reprocessed, but the waste from reprocessing will not be returned to Sweden. Before disposal, the spent fuel is assumed to be encapsulated in a corrosion-resistant canister.

The estimated total amount of fuel consumed in the twelve reactors is calculated to 7 840 tonnes of uranium. The average burnup is approximately 35 000 MWd/tU for the BWR fuel and 39 000 MWd/tU for the PWR fuel. The repository will also handle some fuel from early research and test reactors, but this fuel only has a minor influence on the cost of the repository.

Some long-lived waste from the Studsvik research facility will be disposed of in the repository. The corresponding costs will, however, not be included in the costs given below.

2. Geological medium

The repository for spent nuclear fuel is planned to be built at about 500 meters depth in the Swedish bedrock at a site still to be chosen. The medium will be a hard rock, granite or gneiss, that is found almost everywhere in Sweden.

3. Waste management system

3.1. Overview

The Swedish radioactive waste management system is shown schematically in Figure 1. Low- and intermediate-level short-lived waste is disposed of directly in an underground repository, SFR, at Forsmark.

The spent nuclear fuel is transported, after a minimum of nine months storage in the reactor pools, to a central interim storage facility, CLAB, located close to the Oskarshamn nuclear power plant. In CLAB, the fuel is moved from the transport casks to storage canisters that are stored in pools. CLAB has at present a capacity of almost 5 000 tonnes of uranium and is intended to be enlarged at the beginning of the next century to host all the Swedish spent nuclear fuel, *i.e.*, 8 000 tonnes.

The spent fuel will be stored in CLAB for about 40 years. The fuel is then transported to an encapsulation facility which is assumed to be co-located with the final repository. As the latter has not yet been sited, it is conservatively assumed to be located at a certain distance north of CLAB. The fuel is transported by ship to a nearby harbour and then by rail to the repository site.

3.2. Site services

The spent fuel casks from CLAB are transported to a suitable harbour nearby. In the cost calculations, certain harbour improvements are included, *e.g.*, a new and separate ro/ro quay, a widened and deepend approach channel, a new harbour apron, and guard houses.

The casks are then transported by rail to the repository site. It is assumed that 50 km of new railway will have to be built. In addition, rolling stock, *e.g.*, locomotives and specially built cars, is acquired. These costs will be included in the cost calculation. It should be noted that the costs given below do not include the sea transport costs.

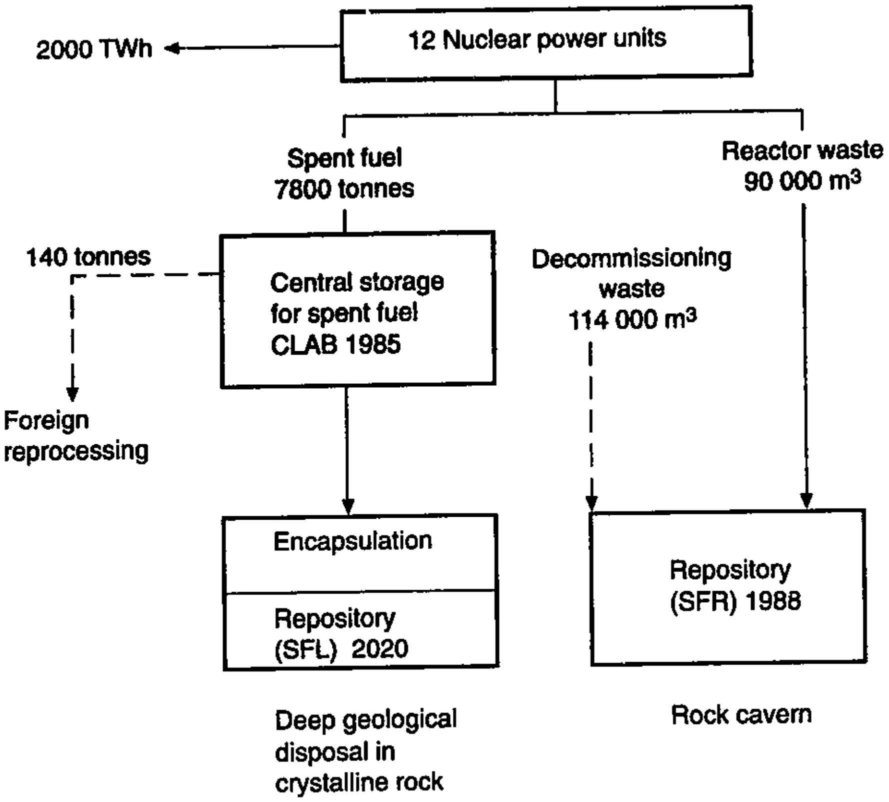
At the repository site, the encapsulation facility is built directly above the repository. In addition, there are personnel facilities including housing, goods reception station, workshops, vehicle service, concrete station with crusher, storage and handling facilities for bentonite, etc. A water supply and sewage system are also included. The total site area is approximately 1 km^2.

The site services operating staff is estimated to amount to 150 persons including all administrative personnel for the site.

3.3. Encapsulation facility

The spent fuel will be received and encapsulated in copper canisters in the encapsulation station. The encapsulation facility is dimensioned to accept about 300 tonnes per year, corresponding to 210 disposal canisters

Figure 1. **Main system for management of radioactive waste in Sweden**



or one canister per working day. The encapsulation facility, which is 170 m long, has a total building volume of 250 000 m³.

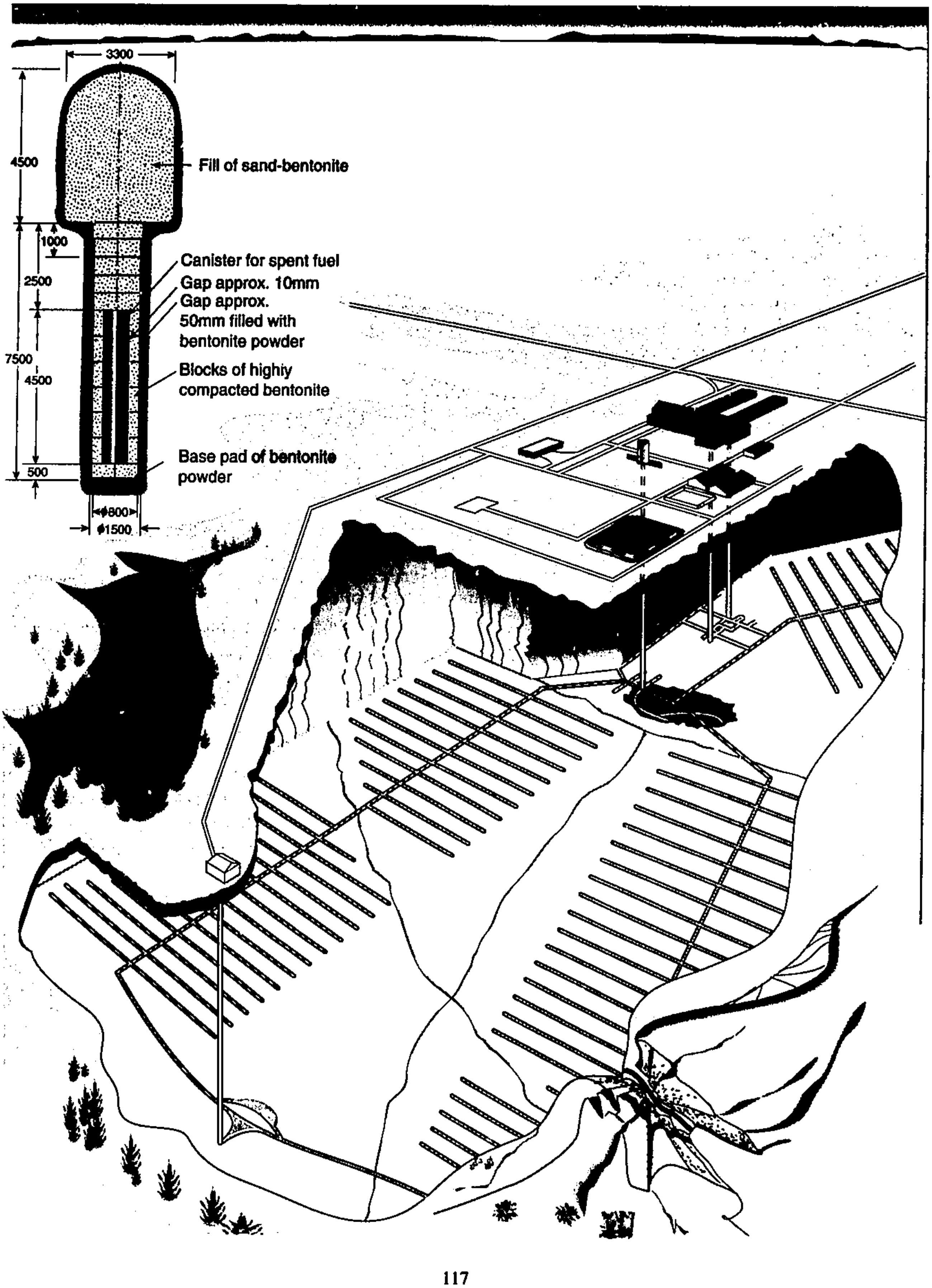
The copper canister is a cylinder 4.5 m long and 0.8 m in diameter. It has a wall thickness of 0.1 m and can accommodate up to nine BWR fuel elements, or about 1.5 tonne of uranium. The actual number of fuel elements per canister is determined by the residual power of the fuel elements. The total power of a canister at disposal shall not exceed 800 W, in order to keep to temperature rise after disposal below 100°C. The void space in the canister is filled with molten lead and the copper lid is welded to the canister by means of electron-beam welding. Fuel channels and core components are put in concrete canisters. The lines for spent fuel encapsulation are duplicated.

The operating staff of the encapsulation facility is expected to number about 80 persons.

3.4. Repository

The repository will be built at about 500 m depth and can be reached via an elevator from the encapsulation facility. The repository consists of parallel deposition tunnels, with a total length of about 40 km, with appurtenant transport tunnels, service areas and four shafts to the ground surface. The waste canisters are deposited in vertical drill holes (5 700 holes) in the bottom of the deposition tunnels. An artist's impression of the repository is shown in Figure 2. The distances between the deposition holes and between the tunnels are determined by the limitation of the maximum allowed temperature and by the rock conditions. Although the maximum allowed temperature in and around the repository is 100°C, in the present design the temperature never exceeds 85°C. The resulting maximum heat load of the repository is 40 kW/ha.

Figure 2. **Final repository for spent fuel, artist's impression**



The repository is divided into two or more parts to permit a physical separation of the deposition work from other activities, such as excavation and sealing. The deposition tunnels will be excavated as deposition proceeds and the tunnels will be backfilled shortly after deposition.

The total excavated rock volume is about 800 000 m^3, of which the deposition tunnels account for about 500 000 m^3. These tunnels have a cross section of about 14 m^2. Conventional tunneling techniques have been assumed.

The waste canisters are transported underground by a deposition vehicle containing a radiation shielding compartment for the canister.

Operation will involve about 120 persons, including teams for deposition, rock excavation and backfilling.

3.5. *Time schedule*

The construction of the disposal facility is planned to start in 2010 and deposition in 2020. Encapsulation and disposal will continue for about 27 years during the period 2020-2046, followed by five years for sealing and decommissioning. No costs for surveillance after closure are included in the cost calculations.

Before 2010, work will begin on R&D, site selection and site characterisation. The costs for these activities are not included in the costs below. The cost for site characterisation and licensing is approximately 1 000 M SEK and for R&D and site selection approximately 3 000 M SEK.

4. Results of cost calculations

4.1. *Purpose of the cost calculations*

The cost calculations that are performed annually are primarily made to provide a basis for determining an adequate fee to be levied on Sweden's nuclear power production to finance back-end activities. In order not to underestimate the fee, the cost calculations are deliberately made in a very conservative way, *e.g.*, concerning assumptions about location, availability of infrastructure, and level of contingencies.

A secondary purpose of the cost calculations is to provide a basis for comparison between different disposal concepts and for optimisation. It should also give guidance to the R&D work concerning the costs for uncertainties.

4.2. *General assumptions*

The cost calculations are performed in the price level of January 1990 and the techniques applied for construction and operation are those generally available today. The work is also performed according to the codes and regulations of today. As far as possible, the experiences acquired from the construction and operation of the interim storage facility and the final repository for low- and intermediate-level waste as well as from the reactors are utilised. Also experience from non-nuclear applications is widely used.

4.3. *Results*

In Table 1, the results are presented separately for the site services, the encapsulation facility and the repository, and split in the cost categories of investment, operation, reinvestment, decommissioning and sealing. In reality, as these activities are going on at one site and to a certain extent in parallel, some difficulties of classification may exist.

The costs are given in million Swedish kronor (M SEK). No discounting has been done. The cost for copper canisters is included in the operations costs and for bentonite in the sealing costs.

4.4. *Contingencies*

As indicated before, the costs given include quite high contingencies. These are of two kinds. First, there are normal contingencies for unforeseen construction work or impreciseness in the definition of the project. These are about 30 per cent. On top of that, a special contingency of about 20 per cent has been added to provide

Table 1. **Summary of cost results for the Swedish spent fuel disposal facility**
M SEK, price level of January 1990[a]

Facility	Site service	Encapsulation	Repository
Cost category			
Investment	3 000	2 800	3 300
Operation	1 500	5 300	600
Reinvestment	200	100	40
Sealing			2 900
Decommissioning	200	300	40
Total	4 800	8 500	6 900

a) No discounting has been done.

for the uncertainty as to whether the disposal facility will be designed in the proposed way. The latter contingency is specifically added to ensure that the fee is not underestimated.

5. Specific results

The total cost given above, 20 200 M SEK, corresponds to 2 630 SEK/kgU or 1.6 M SEK/m^3 of waste or 10 M SEK/TWh. All these figures are undiscounted.

6. Financing system

According to Swedish legislation, the costs for the back-end of the nuclear fuel cycle, including the decommissioning of nuclear power plants, shall be borne by the reactor owners. To cover the future costs, a fee is levied on the nuclear electricity production. The collected fees are paid to the state and collected in funds at the National Bank of Sweden. One fund is set up for each reactor owner. The funds are administered by the National Board for Spent Nuclear Fuel, SKN.

The fee shall be paid as long as the reactors are in operation and should be spread equally over the total production period. The level of the fee is determined annually by the government and is set separately for each reactor station. The decision by the government is based on a proposal by SKN.

The fee is calculated in such a way that it will have the same nominal value over the entire electricity production, that is, it will ideally rise with inflation. Some cautious assumptions are made about the rate of return on invested money and the inflation rate, corresponding to a real rate of interest of 2.5 per cent.

In the 1990 cost calculation, the total costs for the back end are estimated to be 53 G SEK. Of this, 20 G SEK is attributable to final disposal of spent fuel. The total fee for 1990 has on the average been 0.019 SEK/kWh electricity produced in the nuclear power plants. Of this, about 0.007 SEK/kWh corresponds to the final disposal of the spent fuel, which is 2-3 per cent of the electricity production cost.

The total fund content at the end of 1990 was 7.6 G SEK. The money is used for the different waste management activities already under way, such as interim storage, transport, and research and development.

Reference

Swedish Nuclear Fuel and Waste Management Co. (1990), *PLAN 90 - Costs for Management of the Radioactive Waste from Nuclear Power Production,* SKB Technical Report 90-33, Stockholm.

SWITZERLAND

1. General

The Swiss nuclear power system comprises five reactors (two BWRs and three PWRs) with a total net capacity of 2910 MWe. The reactors were brought into operation in the period 1969 to 1984. For the purpose of cost calculation, it is assumed that each reactor will be in operation for a period of 40 years. With this assumption, the total electricity production (for a capacity factor slightly above 80 per cent) from nuclear electricity generation in Switzerland would be 850 TWh.

The strategy currently adopted for the management of spent nuclear fuel is that of reprocessing followed by disposal of the vitrified waste, together with a large proportion of other waste types from reprocessing, as well as other long-lived wastes, after about 40 years of interim storage. Before disposal, the high-level waste (HLW) is assumed to be packaged in corrosion-resistant overpacks at the repository site. The intermediate-level waste (ILW) is solidified at its original sites and no packaging will be performed at the repository site. ILW arising from medical, industry and research activities will also be disposed of in the repository.

With present practices for in-core fuel management, the total amount of fuel consumed in the five reactors during their 40 years lifetime is calculated to be at the very most 4 000 tonnes of uranium, and the burnup characteristics and reprocessing plans mean that at most 3 000 overpacked waste packages, each containing 150 litres of vitrified waste, will have to be disposed of. The total volume of HLW (including overpacks) is estimated to be 4 200 m^3. The total volume of ILW is estimated to be 20 000 m^3.

2. Geological medium

In the feasibility project upon which current cost estimates are based (''Project Gewaehr'' 1985), the reference repository concept is that of disposal of high-level waste in horizontal tunnels at a depth of 1 200 m in the granitic bedrock of northern Switzerland. Other long-lived intermediate-level wastes would be disposed of in large silos within the same repository facility. The repository will be located in a rock with low ground water movement and few major fracture zone.

Further NAGRA work on disposal concepts in sediments is under way, but is not considered in the present cost studies.

3. Reference repository design and features

Figure 1 gives a perspective overview of the repository facility. In this example, the tunnels for HLW disposal are arranged on two levels in a fissured granite block. Figure 2 gives one possible schematic layout of the repository. The repository used for current cost calculations is characterised by the following aspects.

3.1. Surface facility

The waste is prepared for emplacement in the surface reception area. HLW will be additionally packaged in corrosion-resistant overpacks. The current cost calculations are based on the assumption of massive cast steel overpacks. ILW is solidified and packaged in containers at its original sites. All waste – the packaged HLW and the ILW as delivered – is conveyed to the repository with additional transport shielding but **this shielding will be removed from the waste before disposal.**

The surface facilities include reception facilities for receiving the delivered waste, in which the HLW cylinders from reprocessing plants will be packaged in corrosion-resistant overpacks, and some surface buildings.

3.2. Repository

Final disposal of HLW is effected in underground, horizontally mined, parallel tunnels while ILW (bitumized or cemented) is disposed of in underground silos. The tunnels have a circular profile of 3.7 m diameter. No lining is planned. The HLW is emplaced in the tunnels at regular intervals and the remaining space is sealed with bentonite (see Figure 3). The silo caverns have a depth of more than 50 m and a diameter of around

Figure 1. **Perspective overview of reference repository installations for HLW / long-lived ILW. In this example, the tunnels for HLW disposal are on two levels in a fissured granite block. The silos for long-lived ILW are on the right.**

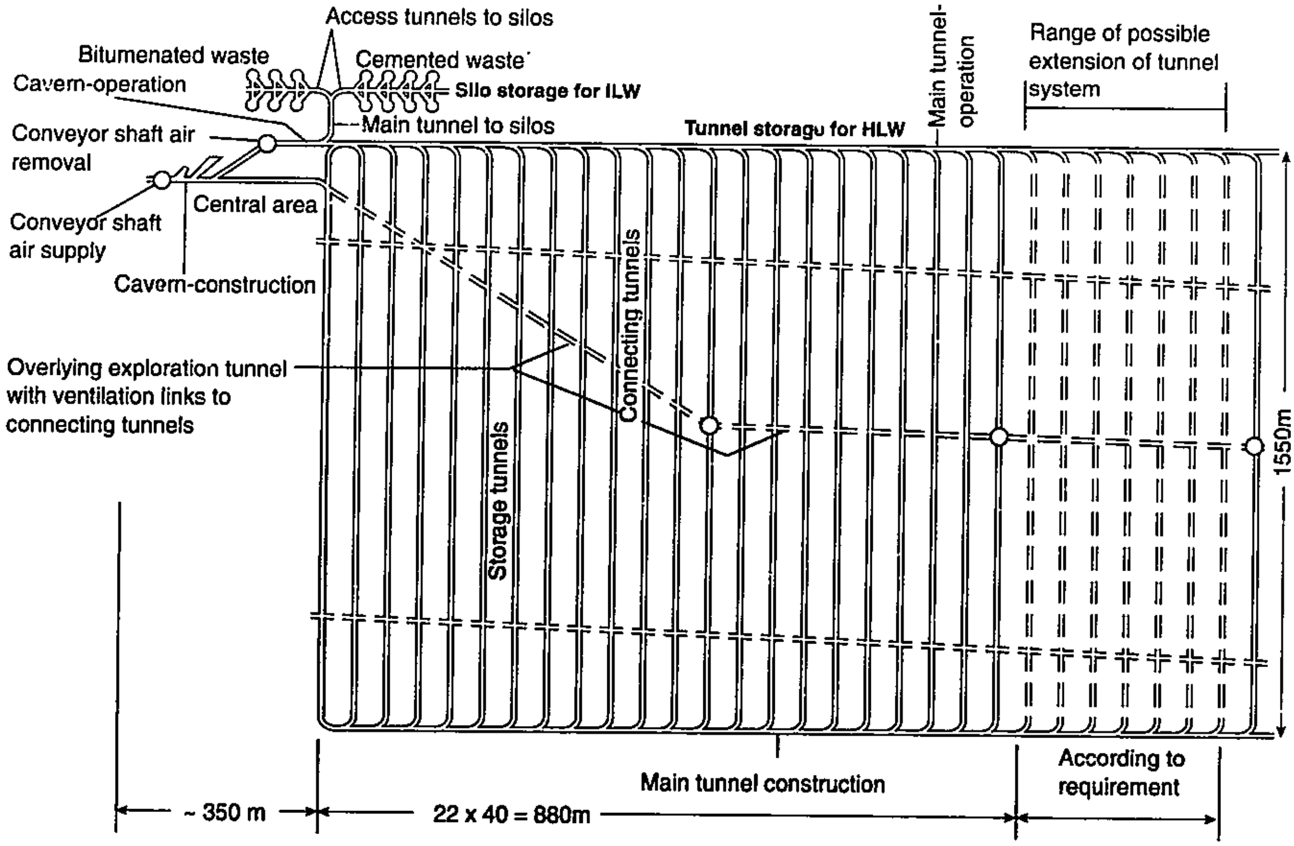
10 m. Each silo has a concrete structure standing free from the rock, and the waste is emplaced and immobilized with special concrete in the structure.

The common entrance to the repository areas is through two vertical shafts (an air inlet shaft and an air outlet shaft). Transportation for construction operations is housed in the air inlet shaft, and the outlet shaft is intended for conveying radioactive waste. An underground central area is planned for organising underground activities.

The silo and tunnel areas are separated in order to avoid any undesirable influence (particularly chemical) of the ILW on the HLW behaviour. The temperature at the overpack outer surface will not exceed 170°C. The ambient rock temperature prior to repository construction is 55°C. The maximum design-base heat load of the repository as a whole is estimated to be 1 750 kW (40-year interim storage after unloading from reactor).

Figure 2. **Schematic representation of repository layout**

The arrangement can be adapted to the specific geometric structure of the host rock in the repository zone, example in Figure 1.



Before final closure of the repository, long-term, in-situ experiments will undergo a technical safety evaluation (observation over several decades during the operational period of the repository). Retrievability of the waste, maintenance and supervision after closure of the repository are not required.

The construction and operational phases of the repository run simultaneously but all work involving the use of explosives will be completed before emplacement of radioactive waste begins.

The total excavated volume of the underground constructions is around 600 000 m^3; the construction period is estimated at about 10 years (up to commencement of emplacement operations excluding the period of geological investigations). The emplacement operations and the simultaneous tunnel excavation require a team of around 200 people.

3.3. *Time schedule*

The cost calculations are based on a scenario in which the exploration/ site characterisation will continue from the mid-1980s to about 2000, followed by a period of at least 20 years for the preparation for site licensing, for permission as well as construction of the repository itself. The operational phase follows for a period of 20 years, although this time can be varied.

Figure 2. **Schematic representation of repository layout**

The arrangement can be adapted to the specific geometric structure of the host rock in the repository zone, example in Figure 1.

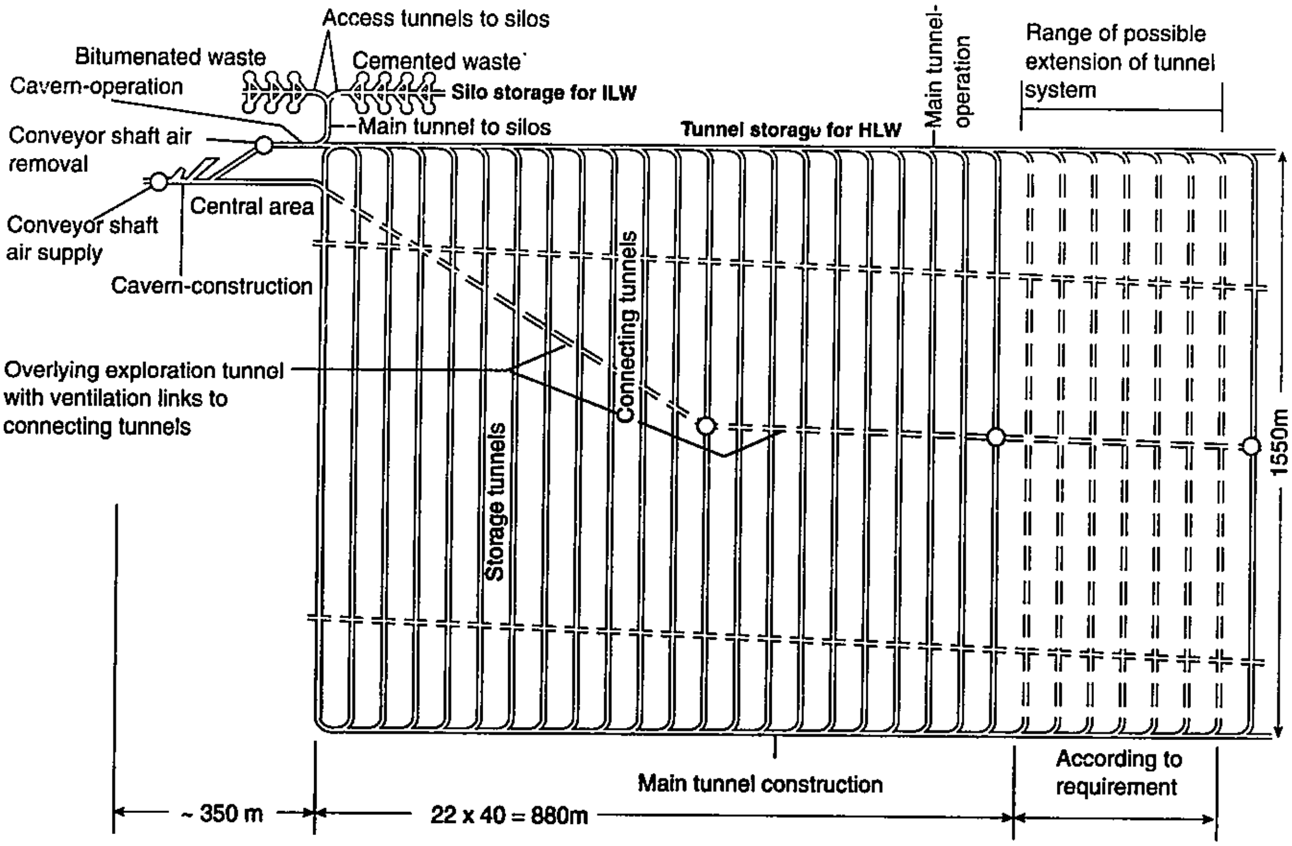


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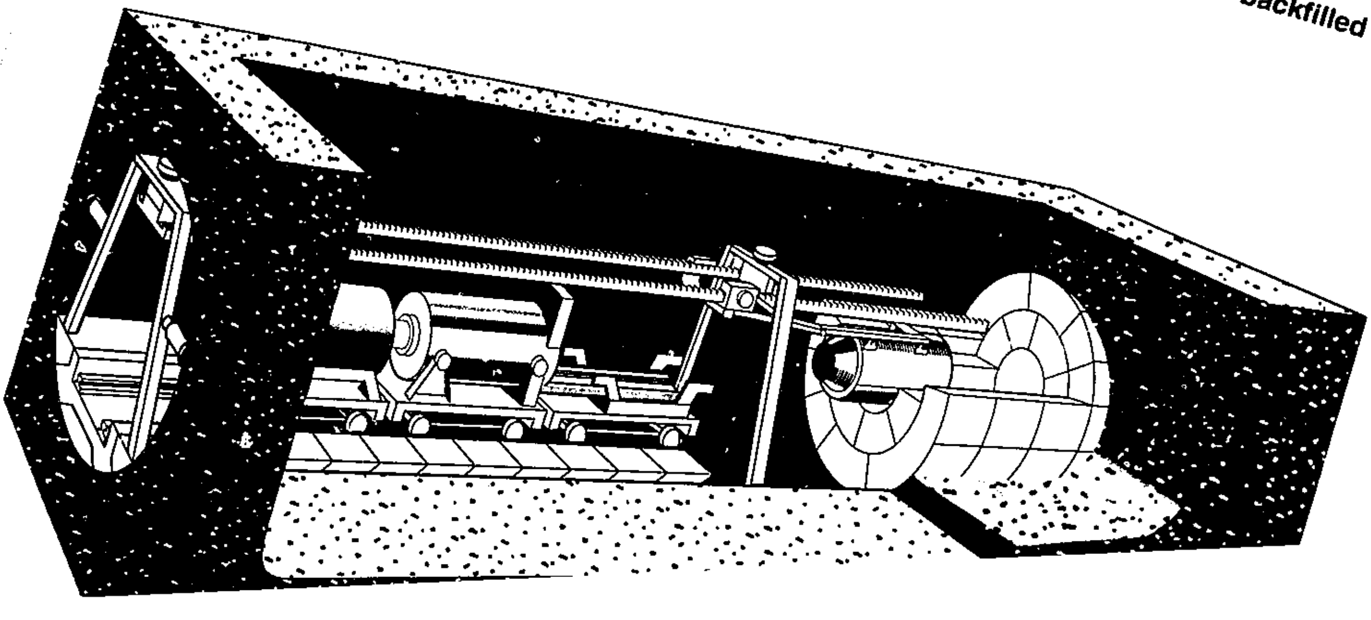
Figure 3. **Emplacement procedure for overpacks containing vitrified HLW in the disposal tunnels. The space between the overpack and the tunnel wall is backfilled with blocks of compacted bentonite.**



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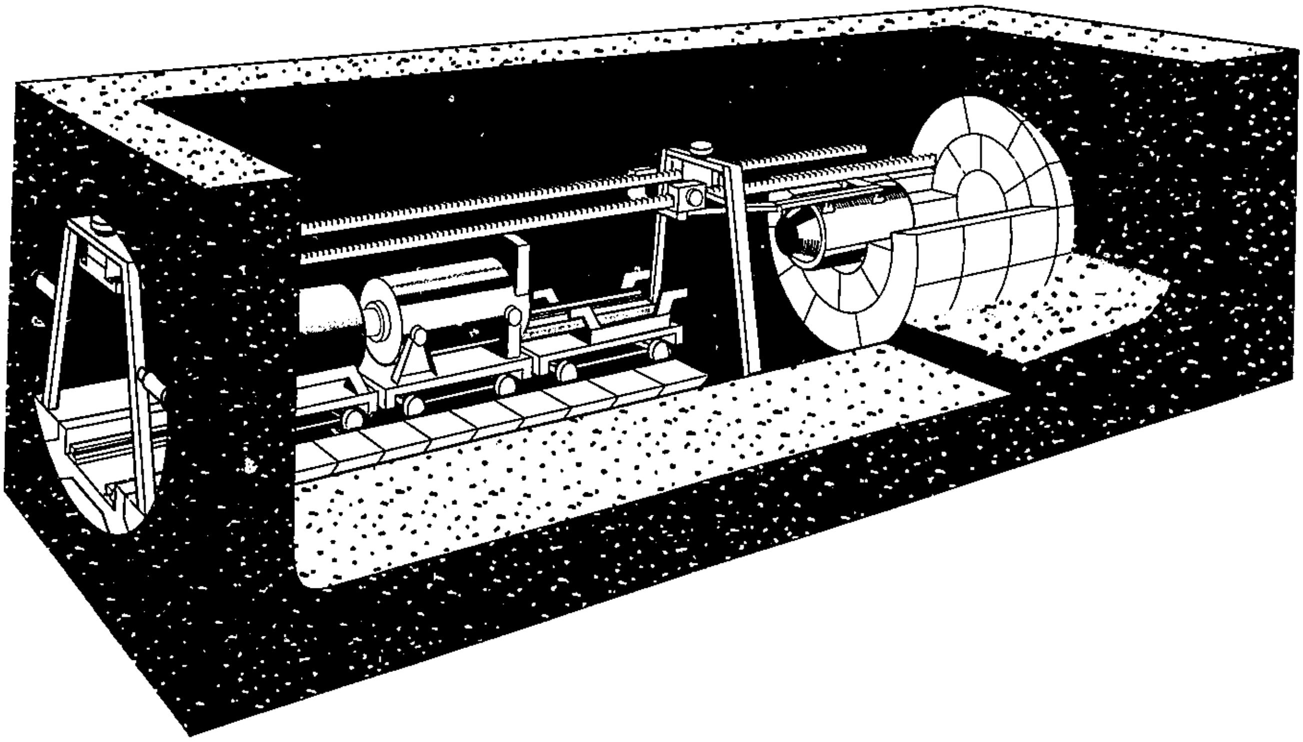


4. Results of cost calculations

4.1. Purpose of the cost calculations

The cost calculations performed thus far were primarily made to provide a basis for the utilities and the federal government to ensure that sufficient reserves are made for financing back-end activities. In order not to underestimate the fee, the cost calculations are deliberately made in a conservative way. Furthermore, the present basic design of the repository is not optimised and is very conservative from the cost point of view.

A secondary purpose of the cost calculations is to provide a basis for comparison between different disposal concepts and for optimisation. It should also give guidance to the R&D work, indicating where efforts to reduce costs should be concentrated.

4.2. General assumptions

The costs are calculated at the price level of January 1990, and the techniques applied for construction and operation are those generally available today. The work is also performed according to the codes and regulations of today. As far as possible, experience from the construction of similar underground projects, such as road or railway tunnels, as well as from nuclear power plant construction, has been used.

Even though the costs are spread over quite a long time period, no discounting or inflation is considered in the cost calculations. Nor is the possible increase in productivity or change in technology considered.

4.3. Results

The results of the cost calculations are presented in the Table 1. The costs are given in M SF, million Swiss francs. No discounting has been done.

"Cost up to start of construction" includes the costs for R&D, site investigation, site evaluation, repository design, licensing and others. The costs for the cast steel overpacks are included in "Operation of repository". The costs for construction, operation and decommissioning total 1 950 M SF. The costs are not separated between the surface and underground installations.

Table 1. **Rough breakdown of costs for the Swiss base case scenario**
HLW – ILW repository, in M SF price level January 1990[a]

Cost up to start of construction (including exploratory shaft, which will be integrated in the facility)	900
Construction costs	870
Operation of repository	800
Sealing and recultivation costs	280
Total	2 850

a) No discounting has been done.

4.4. Contingencies

In the Swiss cost estimate, contingencies are not specified directly but are implicitly included in the conservative budgeting involved.

5. Specific results

The total cost given above, 2 850 M SF, corresponds to 710 SF/kgU or 0.68 M SF/m^3 of HLW (including overpacks) or 3.4 M SF/TWh. All these figures are undiscounted.

It should be noted that these figures include the costs for site selection and R&D (900 M SF). When these costs are reduced from the total, the unit cost becomes 2.3 M SF/TWh; 440 SF/kgU; 0.46 M SF/m^3 HLW.

6. Financing system

Waste producers are responsible for the costs of final disposal, so that the individual utilities must set up their own reserves to meet this liability. This means that the individual utilities and the federal government (which is responsible for the long-lived ILW from outside the nuclear industry) must respectively make individual assumptions as to the appropriate rate of discount and other financial parameters.

UNITED KINGDOM

1. General

1.1. Introduction

In the UK, high-level waste (HLW) will be disposed of in a deep underground repository. Some outline design studies, which include cost estimation, were undertaken [1, 2]. Further studies have now been carried out. These give new cost estimates based on the latest information from a detailed intermediate-level waste (ILW) study undertaken by UK Nirex, with appropriate adjustments being made for the differences between ILW and HLW disposal. This Annex provides the results of this new study.

There are uncertainties regarding future nuclear power policies within the UK. The approach adopted in the study has thus been to assume a nuclear power programme and particular reprocessing policy as an "example case", and also to consider a range of other nuclear power programmes and spent fuel management policies. The study provides a cost algorithm that can be evaluated for any required case within stated limits, be it the example case or any other.

1.2. UK nuclear power programme assumed in the example case

The reference nuclear power programme consists of 45 existing plants, one PWR under construction at Sizewell B and eight PWRs to be constructed in the future. All the VHLW and spent nuclear fuel produced by the operation of these facilities are assumed to be disposed of in a repository. The programme may be summarised as follows:

- Commercial reactors: 26 Magnox (4 of them are being decommissioned), approx. 4.5 GWe; 14 advanced gas-cooled reactor (AGR), approx. 8.5 GWe; one PWR (under construction), approx. 1.2 GWe. Assumed operational lifetimes are 30 to 40 years for the Magnox, 25 to 30 years for the AGR and 40 years for the PWR.
- Experimental/demonstration reactors: one fast reactor (PFR); one high-temperature reactor (HTR); one steam-generating heavy water reactor (SGHWR); one Windscale advanced gas-cooled reactor (WAGR). The last three are being decommissioned. HTR produced heat only. PFR, SGHWR and WAGR had a combined capacity of approx. 0.4 GWe.
- Future reactors: it is assumed that the UK nuclear economy will continue at around 50 TWh/year at least until the middle of the next century. This will require an additional eight PWRs, totalling 9.6 GWe.

2. Geological medium

A wide variety of geology is available in the UK. At present no significant work has been done to select a site for the HLW repository and all declared geological characteristics must be considered speculative. The latest work assumes an unfractured granite host geology. Some of the assumed geological parameters are:

Depth	1000 m
Host rock temperature limit	100°C
Thermal conductivity	2.5 W/(m.K)
Specific heat	850 J/(kg.K)

It should be noted that, in practice, a lower limiting temperature (60°C) relating to canister metal corrosion rather than host rock may be relevant.

3. Waste management strategy

3.1. General situation

In the UK, radioactive wastes are divided into three categories:

- LLW, low-level waste, less than 4 GBq/Mg alpha or 12 GBq/Mg beta-gamma;
- ILW, intermediate-level waste, more active than LLW;
- HLW, high-level waste, as for ILW but having a rate of heat emission that requires consideration for design of management facilities.

Disposal of most LLW has always been available at Drigg (NW England, 5 km from Sellafield) in near-surface trenches excavated in clay, and more recently in near-surface concrete vaults. This facility is likely to be available well into the next century (approx. 2050).

Nirex has been charged by government with the responsibility for bringing forward proposals for the disposal of ILW and LLW in a deep disposal facility to be operational by 2005. Following the results of their geological investigations, Nirex are now concentrating their resources in the vicinity of the Sellafield site.

At that stage, the UK will only lack a repository for HLW, currently comprising vitrified fission products. It would also include fuel to be sent directly for disposal if such a policy were to be adopted. In the UK, vitrified HLW is stored for at least 50 years, at the end of which period disposal options will be considered [3].

3.2. Spent fuel management policy in the example case

The example case assumes the reprocessing of all commercial fuel and that from PFR. The HLW from fuel reprocessing is to be vitrified into stainless steel canisters and kept in the Vitrified Product Store (VPS) at Sellafield or in similar stores until the deep repository is in operation. HTR and SGHWR fuels are assumed to be stored until the repository is in operation and then to be directly disposed of. It is assumed that only these vitrified wastes and spent fuel will be disposed of in the repository.

The amounts of spent fuel and VHLW for the example case and corresponding heat outputs at various time-scales are summarised in Table 1. The total quantity of the waste is equivalent to 70 000 tU. The waste projection based on the example case is reasonably conservative because of the minimum number of HLW canisters that could arise in the UK unless there were an early closure of the industry. The cost algorithm provided in Section 6 allows the cost evaluation for other cases.

Table 1. **UK waste characteristics – Canister numbers and heat output at particular dates**

HLW Category	Number of canisters	Heat Output in MW		
		Year 2050	Year 2100[a]	Year 2200
Magnox and AGR (VHLW)	7 720	2.70	0.97	0.24
One PWR (VHLW)	670	0.60	0.20	0.05
PFR (VHLW), HTR & SGHWR (spent fuel)	820	0.10	0.09	0.06
PWR & BWR (VHLW)[b]	600	0.30	0.14	0.07
Eight future PWR (VHLW)	5 360	6.20	2.20	0.46
Total	15 170	9.90	3.60	0.88

a) Example case repository closure date.

b) Indicative data for wastes arising from overseas reprocessing contracts secured before 1976, for which there is no provision for return of wastes.

AGR	Advanced Gas-cooled Reactor
BWR	Boiling Water Reactor
HTR	High Temperature Reactor (Dragon)
PWR	Pressurised Water Reactor
SGHWR	Steam Generating Heavy Water Reactor
VHLW	Vitrified High Level Waste

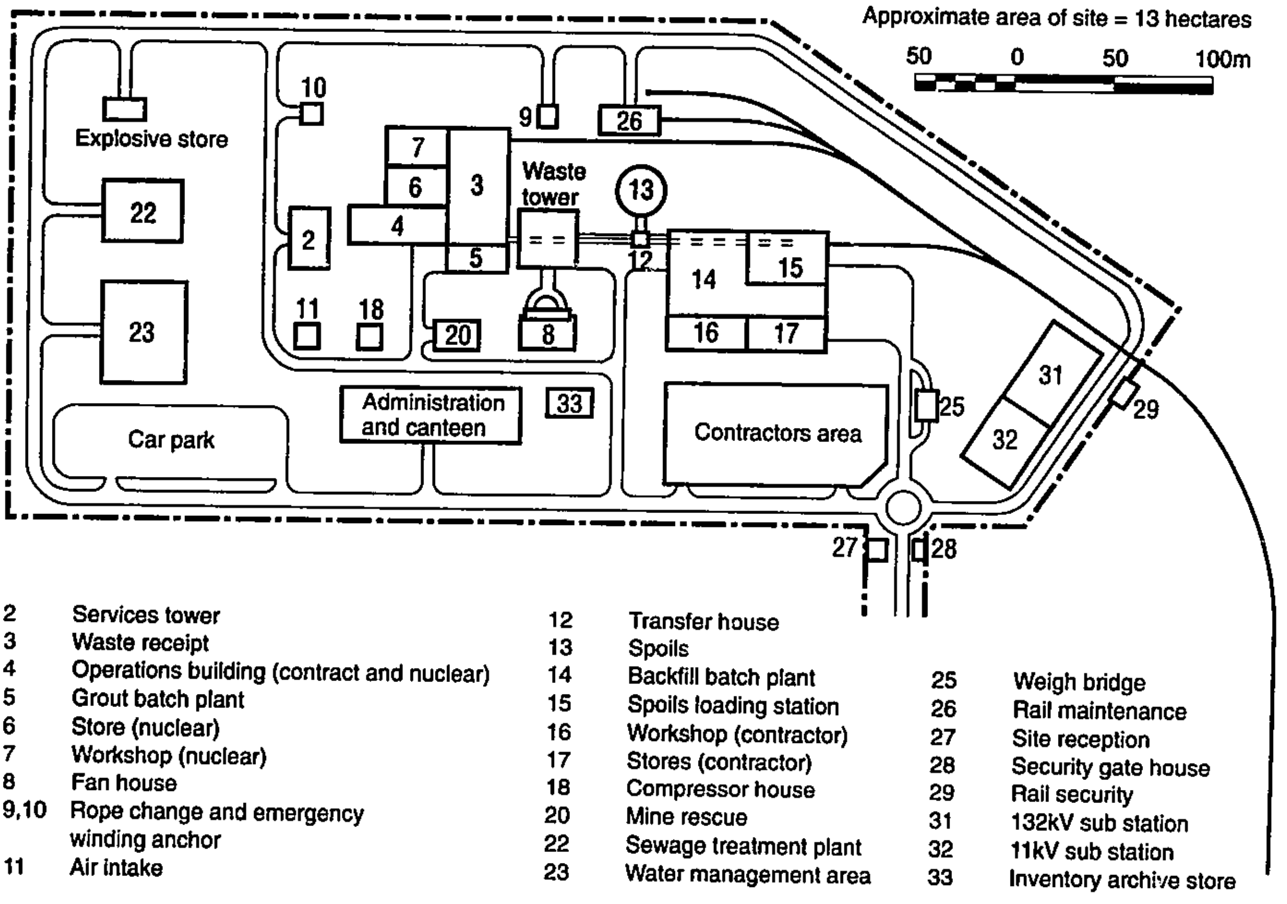
4. Waste management systems

At some time during the storage period for fuel destined for direct disposal, it is assumed for this study that plants will be built to dismantle and package the fuel into stainless steel canisters on some of the storage sites. The canisters are assumed to have the same general design as the canisters for vitrified waste blocks. The glass block has a volume of 150 L and the canister an external volume of just less than 200 L. Neither the costs of vitrification nor the costs of encapsulating fuel in canisters are included in the cost figures given here. Canisters will be transferred by rail from the site of origin to the repository in a modified fuel flask.

The repository surface establishment (or Headworks Site) is shown on Figure 1. Here the canisters will be placed into 65-mm-thick mild steel overpacks, which act as a corrosion-retarding barrier, and will then be placed into the site transfer flask. The disposal costs of canisters with and without overpacks can be determined from the cost algorithm as given in Section 6.

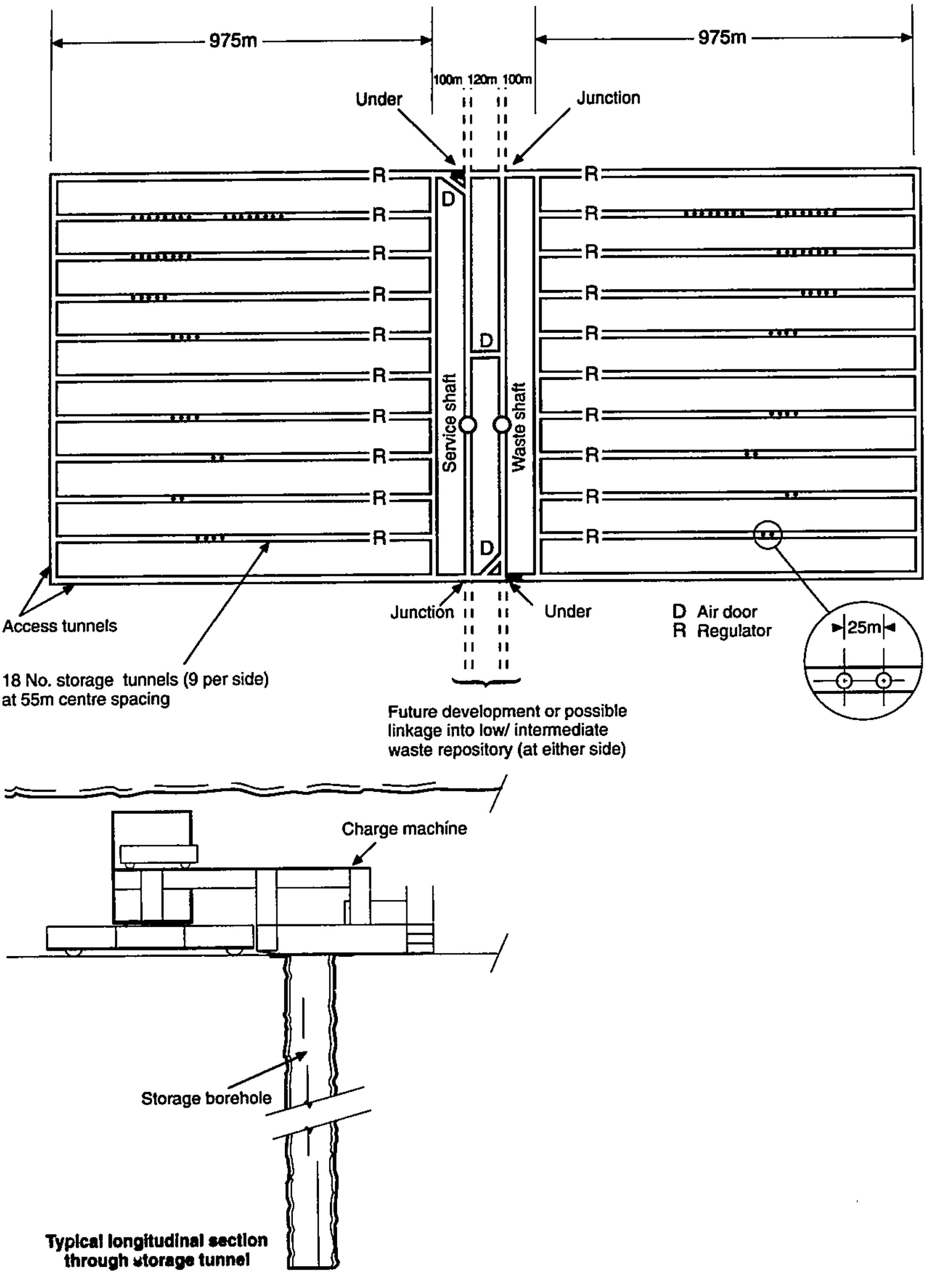
The repository surface facilities will be connected to the disposal level, 1 000 m below ground, by a 6-m-diameter service shaft and an 8-m-diameter hoist shaft for lowering the waste. A schematic diagram of the disposal level is shown on Figure 2, although the example case has 15 pairs of disposal tunnels rather than 9 pairs shown. The waste will be emplaced in 30-m-deep boreholes vertically drilled in the tunnel floor. The total excavated rock volume for the repository in the example case is estimated to be 1.4 million m^3. The maximum design heat load of the repository is 24 kW/ha.

Figure 1. **Headworks site layout**



2	Services tower	12	Transfer house		
3	Waste receipt	13	Spoils		
4	Operations building (contract and nuclear)	14	Backfill batch plant	25	Weigh bridge
5	Grout batch plant	15	Spoils loading station	26	Rail maintenance
6	Store (nuclear)	16	Workshop (contractor)	27	Site reception
7	Workshop (nuclear)	17	Stores (contractor)	28	Security gate house
8	Fan house	18	Compressor house	29	Rail security
9,10	Rope change and emergency winding anchor	20	Mine rescue	31	132kV sub station
		22	Sewage treatment plant	32	11kV sub station
11	Air intake	23	Water management area	33	Inventory archive store

Figure 2. **Layout of underground repository**



Typical longitudinal section through storage tunnel

5. Time schedule

The example case assumes a time schedule described below:

a) repository closure date of 2100;
b) 20-year operational lifetime of the repository;
c) backfilling and sealing of the repository after the operational phase.

The operating lifetime of 20 years is a practical figure which minimises fixed operating costs. An operational phase of 50 years has also been assessed as another case emphasizing conservatism and flexibility.

6. Cost calculations

The total cost of the repository for the example case has been estimated by considering the following steps in high level waste management:

a) repository "front-end" (pre-construction) procedures;
b) waste transport to the repository;
c) overpacking the canisters at the repository headworks;
d) constructing, operating and ultimately dismantling the repository headworks;
e) constructing, operating and ultimately closing and sealing the underground works at the repository.

The component cost items of "Front End Procedures" are site investigations (including geotechnical work), engineering costs (excluding detail design), research and development, underground laboratory marginal construction cost and operation costs, transport and packaging studies, public relations, public inquiry, and company administration and staff costs.

The component cost items of "Transport" are flasks, rail wagons, loading costs, and movement costs. Overpack procurement is the component cost item of "Overpacking".

The component cost items of "Headworks Costs" are site preparation, buildings and equipment, services (water, sewage, electricity, etc.), salaries and staff overheads, and decommissioning. The component cost items of "Underground Works" are shafts and associated infrastructure, access tunnels, storage tunnels, boreholes, and final backfilling and sealing.

A cost algorithm has been derived, based on the above component cost items. These are aggregated into volume-dependent, time-dependent, heat-dependent and fixed terms. The algorithm gives the undiscounted cost in 1991 pounds sterling. The cost described is the base cost plus contingency. Contingency allows for small undercounts and the resolution of minor difficulties in the project. The data provided here do not include risk margin to cover changes in specification or major movements in contractor charges.

Total cost in 1991 M £

$$= N\,(0.01035 - 0.002586P) + H\,(0.1505 - 0.1009P) + t\,(0.5 + 3.06D) + (315.4 + 517D - 6.1P)$$

Where:

N = number of canisters
H = total heat output in kW at repository closure
t = repository operating lifetime in years

And where the absence or presence of particular items is indicated thus:

$D = 1$ for a purpose-built HLW-only repository
$D = 0$ for the marginal cost of an HLW scheme at an ILW repository site
$P = 1$ where 65 mm steel overpacks are used
$P = 0$ where canisters are emplaced without overpacking

The algorithm was developed for ranges of the variables set out below. Calculations made with the variables set beyond these ranges should be treated with caution.

$9820 < N < 36060$; $1400 < H < 12400$; $20 < t < 50$

The costs of the example case are presented in Table 2. These costs are not discounted. As with the costs from the algorithm, contingency is included at various rates for different sorts of costs, equivalent to an average of approximately 25 per cent overall. No risk margin has been added here, although at the current state of the work a 33 per cent risk margin is considered appropriate.

Table 2. **Repository costs – Major components and totals**
Base cost plus contingency – of the example case[a]

Major costs components	M £ 1991 money value
Front end (including underground laboratory)	450
Packaging	29
Transport	12
Headworks (including inventory archive)	311
Underground works	392
Total	1 194

a) The example case assumes disposal of 15 170 overpacked canisters in a purpose-built repository for the sole use of HLW, operating from 2081 to 2100, with a heat output at closure of 3 600 kW.

According to the discussion in Chapter 4 of the main report, the disposal and encapsulation cost, which are compared in this report with cost estimates of other countries, should not include the costs for research and development (R&D) and site selection. Therefore, the disposal and encapsulation costs quoted in the main report should be £ 1 000 M.

7. Specific results

The total cost of £1 194 M (1991 money value) is equivalent to £79 000 per canister disposed of. This corresponds to a volume unit cost of £400 000/m^3 when based on the canister external volume. This also corresponds to a unit cost of £17/kgU when based on the quantity of uranium money value and all dollar costs at July 1991 money value in the original spent fuels. In this section, all sterling costs are January 1991.

The electricity anticipated to be produced from all committed reactors in the reference programme is approximately 2 000 TWhe, with the electricity associated with the overseas waste adding just over 10 per cent; in addition, the eight further PWRs will produce 2 160 TWhe, totalling 4 300 TWhe. It follows that the charge to a kWh unit of electricity is £0.00027 [0.45 US mill] on a simple division basis. When the repository cash flow has been discounted and levelised at 5 per cent, it gives a charge per canister of £163 000. When this has been discounted at the long-term provision rate of 2 per cent to a base date, and the present worth of the electricity associated with the canister has been calculated at 2 per cent to the same base date, the real cost to a unit of electricity may be found by dividing one into the other. The cost is £0.0001/kWh or 0.17 US mill.

The scope of the main report includes consideration of the disposal of ILW arising from reprocessing. In practice, in the UK, ILW is currently assumed to be disposed of in a separate repository from HLW and thus the costing of such disposal is an entirely separate issue. The current cost estimate for Magnox and AGR reprocessing ILW has been converted to a cost per canister supplementary to the £79 000 for the VHLW already calculated above. This supplementary cost is approximately £65 000. This supplement relates exclusively to the 7 700 canisters of Magnox and AGR vitrified waste and gives a total supplement of £500 M. It should be noted that this supplementary cost also includes the costs for R&D, site investigation and waste transport outside the repository.

8. Financing system

UK organisations with long term liabilities for HLW and other types of radioactive waste are each responsible for ensuring that they will be able to meet their liabilities when they arise. Internal financing arrangements are used rather than trust funds or government sinking funds. Nuclear companies calculate their likely future waste management costs including repository fees. Once the size of the total liability has been established, it is discounted where appropriate at a prudent (low) rate. Then a charge is made on the profit-and-loss account for the additional liabilities from the year just finished and any change in technical scope to the discounted liabilities to the end of the previous year. This difference is transferred to the company's accumulated provisions. There is usually a further charge on the profit-and-loss account to augment earlier provisions to allow for inflation and a margin for real rate of return (interest).

The choice of discount rate (or internal rate of return) to evaluate a repository (or other major project) would depend on the financial practice in a particular organisation. At present, in the UK, between 2 and 5 per cent would cover financing, depending on the financial standing of the borrower. Financing and company profit together would require a discount rate in the range of 8 to at least 12 per cent.

References

1. Sir William Halcrow and Partners (1982), *Repository Schemes for High Level Waste Disposal - Review of Schemes for Argillaceous and Saliferous Formations*, United Kingdom Department of the Environment. Report No. DoE/RW/82.017.
2. Seltrust Engineering Ltd., *Engineering Studies of High Level Waste Repositories Task 3 - Review of Underground Handling and Emplacement*, United Kingdom Department of the Environment. Report No. DGR/481/218, February 1981.
3. Her Majesty's Stationery Office (1986), *Radioactive Waste. The Government's Response to the Environment Committee's Report* (Command 9852), London.

UNITED STATES

1. Boundary conditions

Spent fuel generated by commercial nuclear reactors will be the dominant waste form. Spent-fuel projections and the ongoing fee revenue used in this analysis were derived from the no-new-orders projection of spent fuel discharges prepared in 1988 by the United States Department of Energy (DOE). The no-new-orders forecast is based on the assumption that no orders for new reactors will be placed and that only reactors currently under active construction will be completed, *i.e.*, 120 commercial nuclear reactors in total. It was also assumed that commercial nuclear units will operate for 40 years from the issuance of their operating licenses, that reactor performance will not be affected by aging, and that the equilibrium-cycle capacity factor will increase gradually from 60 to 65 per cent in 2000 then to 70 per cent in 2020. Total electricity generated from commercial nuclear reactors is estimated to be 23 004 TWh. The corresponding quantity of spent fuel is estimated to be 86 757 metric tons of heavy metal (MTHM), of which two thirds is from PWRs and one third from BWRs. It is assumed that the spent fuel will be at least five years of age before it is accepted into the repository.

In addition, a total of 17 750 metal canisters with overpacks (about 8 875 MTHM) of defense high-level waste (DHLW) and 300 metal canisters with overpacks (about 640 MTHM) of commercial high-level waste from the West Valley Demonstration Project will be disposed of in the repository.

2. Geological medium

The Yucca Mountain site in Nevada has been designated by law to be the site where scientific investigations will be conducted to determine whether the site is suitable for the development of a repository. Yucca Mountain is underlain by a sequence of silicic volcanic rocks from more than 3 000 to about 10 000 feet thick. The water table is very deep, as much as 2 500 feet below the land surface. The underground repository would be constructed at a depth about 1 000 feet below the eastern flank of Yucca Mountain. The primary area for the underground repository is in the welded tuff.

3. Waste management system

3.1. Overview

Spent fuel will be loaded into transportation casks at the reactor sites for shipment by rail, barge, or truck to the appropriate waste management facility. It is assumed that the spent fuel will be in the form of intact fuel assemblies. A monitored retrievable storage (MRS) will serve as a central facility for temporarily storing spent fuel, retrieving spent fuel, and staging shipments to the repository. Spent fuel will be shipped by dedicated rail from the MRS facility to the repository. The spent fuel will be prepared for disposal by loading it into disposal canisters at the repository site. No overpacks are needed.

DHLW will be vitrified into metal canisters at the defense sites. West Valley high-level waste (WVHLW) or commercial high-level waste will be solidified in borosilicate glass in metal canisters prior to shipment. DHLW and WVHLW will be shipped by rail in transport casks directly to the repository, where the metal canisters will be loaded into overpacks and emplaced in the repository.

3.2. Repository surface facilities

The purpose of the surface facilities is to receive the waste and to prepare it for permanent disposal underground. The central surface-facilities area would be divided into three distinct functional areas used for waste receiving and inspection, waste operations and general support facilities. The waste operation area contains a waste-handling building (WHB). In the WHB, the spent fuel would be unloaded from the shipping cask and transferred to a packaging station, where it would be loaded into canisters. The loaded disposal canisters would be sealed and then stored temporarily in a vault until they were taken underground.

The disposal canister is assumed to be a cylinder 15 to 16 feet long and about 28 inches in diameter, and be fabricated from $^3/_8$th inch stainless steel. The canister is assumed to hold either 4 PWR assemblies, 10 BWR assemblies, or a combination of 3 PWR and 4 BWR assemblies. The heat capacity of the disposal canister is 3.5 kW per canister. The DHLW is placed in a stainless steel canister at the defense sites and loaded into an overpack at the repository site prior to emplacement.

Other planned surface facilities include those for testing performance of waste packages, the decontamination building and waste (produced at the repository) treatment building. In addition, there would be support facilities to provide such services as security, fire protection, administration, maintenance and laboratories.

The repository is assumed to have an annual acceptance rate of 3 000 MTHM of spent fuel and 400 MTHM of high-level waste. During the emplacement phase, the average operating staff for the surface facilities is 627 full-time equivalents.

3.3. Repository underground facilities

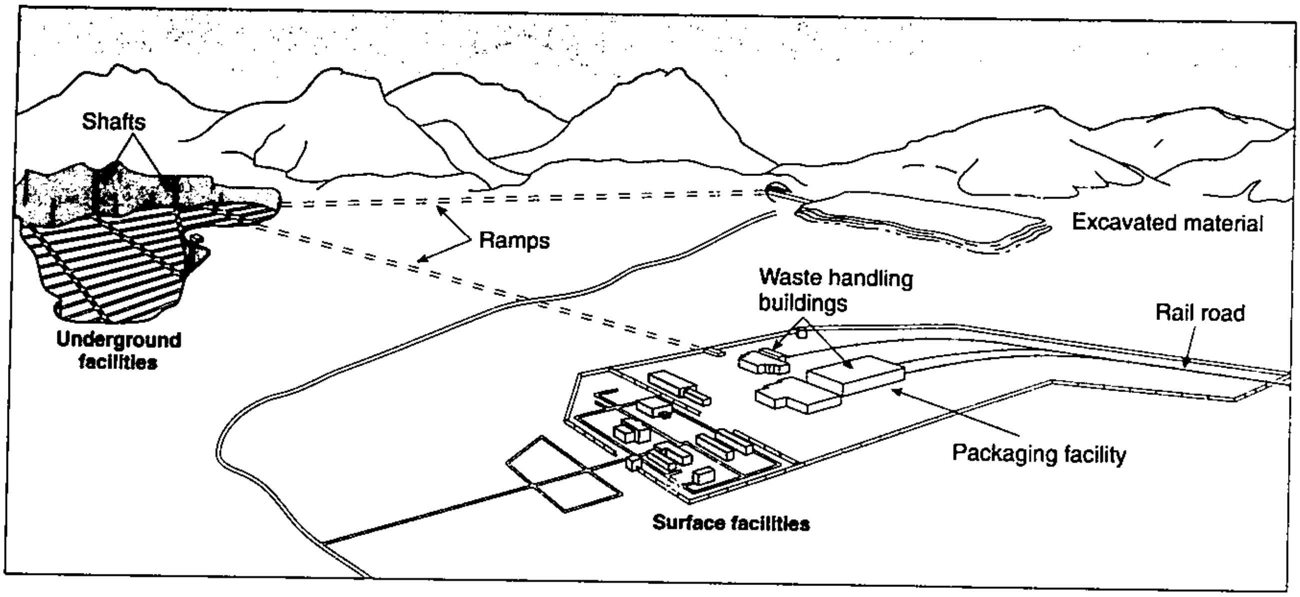
Figure 1 illustrates the planned layout of the repository. The surface facilities would be connected to the underground repository through two ramps and five shafts. The ramps would be mainly used to transport the waste disposal canisters and overpacks and excavated material. They would also serve as ventilation pathways. All five shafts would also be used as ventilation pathways. In addition, one shaft would be used for men and material transport. The repository would have two independent ventilation systems: one for the development of the repository and the other for waste emplacement operations.

Three parallel main entry drifts would extend through the underground facility to provide access to the waste emplacement areas, called "emplacement panels". It is assumed that the waste would be emplaced in vertical boreholes drilled into the floor of the waste emplacement panels. The spent fuel boreholes would be about 25 feet deep, 30 inches in diameter, and the pitch (center-to-center spacing) is fixed at 15 feet. A single disposal canister of waste would be emplaced in each borehole. The DHLW overpack is emplaced in vertical boreholes 20 feet deep, 29 inches in diameter and located between the spent fuel boreholes (commingling). Figure 2 illustrates a schematic of the proposed vertical waste emplacement borehole.

The total excavated rock volume for the repository is estimated to be about 9.1 million m^3, of which about 8.9 million m^3 represent the emplacement area volume. DOE plans to use a combination of drilling and blasting and mechanical mining techniques, *e.g.*, tunnel-boring machines for the excavation of the repository. During the emplacement phase, the average operating staff for the underground portion of the repository is 478 full-time equivalents.

The current conceptual design of the Yucca Mountain candidate repository site was based on an assumed heat-load of 141 kW/ha. Studies have shown that this heat-load satisfies the following temperature constraints: the rock temperature will be less than 200°C one meter from the borehole wall to maintain near-field rock-mass integrity; the rock temperature will be less than 275°C at the borehole wall to maintain spent fuel cladding integrity; and changes in the surface temperature will be limited to less than 6°C to restrict surface uplift changes to less than 0.5 cm/year and meet environmental considerations.

Figure 1. **Planned layout of repository**



3.4. *Time schedule*

The initial acceptance of spent fuel at the MRS facility is assumed to begin in 1998. A full-capability MRS facility is then assumed to be operational in 2000. The repository is assumed to begin operation in 2010. The last discharge of spent fuel for the no-new-orders projection is in 2037. Since the minimum cooling age of the spent fuel is five years after discharge, the waste management system will continue to accept waste until 2042. After all waste is emplaced, a caretaker period will begin so that the Nuclear Regulatory Commission (NRC) requirement that the waste be retrievable for 50 years after the start of waste acceptance can be met. The closure and decommissioning of the repository is assumed to be completed in 2075.

4. Results of cost calculations

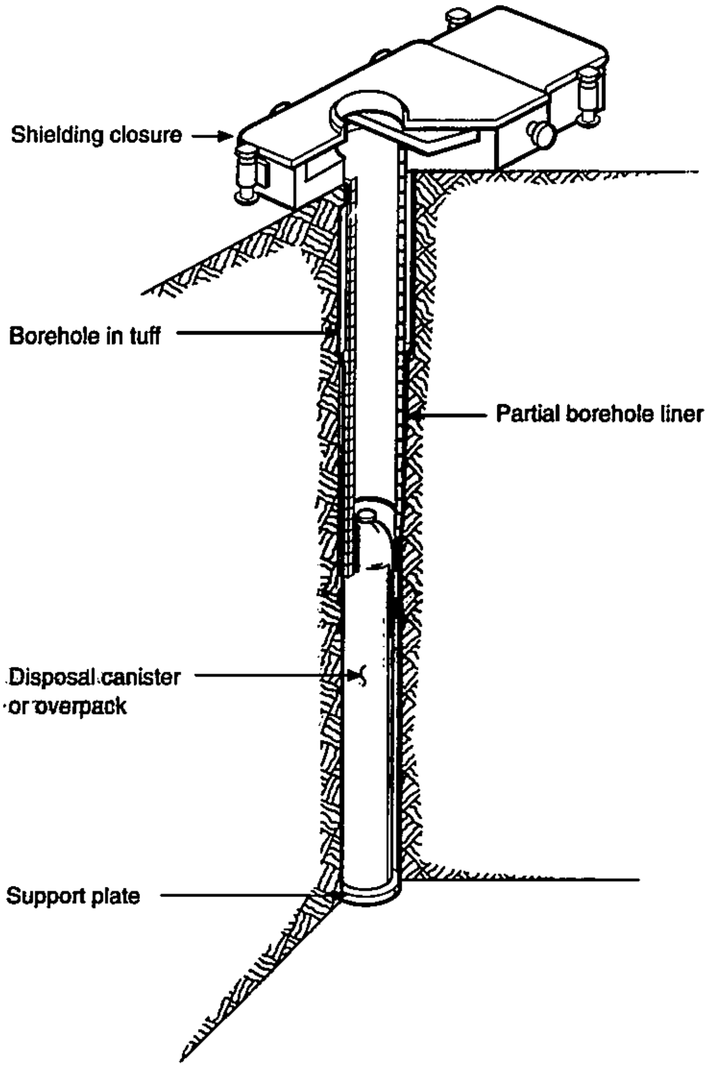
4.1. *Purpose of the cost calculations*

Each year, a comprehensive analysis of the total-system life-cycle cost (TSLCC) of the radioactive waste management system is performed as a reference planning document that aids in financial planning for the DOE's Office of Civilian Radioactive Waste Management Program. The primary use for the TSLCC analysis is to help determine whether the fees paid by waste generators will be sufficient to cover the costs of the program fully. This section provides the results of the TSLCC estimates published in December 1990 (in constant 1988 dollars).

4.2. *General assumptions*

In general, the cost analysis is based on a single set of engineering assumptions. The assumptions used have not been baselined and cannot be interpreted as system requirements. The costs are presented for three scenarios, each of which assumes that waste will be emplaced in either one or two repositories. In the single repository system, all waste is assumed to be emplaced in the Yucca Mountain site in welded tuff. In the two-repository system, 70 000 MTHM of waste are assumed to be emplaced at Yucca Mountain while the remaining

Figure 2. **Vertical waste emplacement borehole**



waste is assumed to be emplaced in a second repository as yet unspecified. For costing purposes, the second repository is assumed to have "generic" geologic conditions.

A higher spent nuclear fuel forecast (the "upper" reference case forecast) consisting of 97 000 MTHM is considered in one of the three scenarios. The no-new-orders forecast (see Section 1) is considered in the other two scenarios. All costs are presented in constant 1988 dollars, undiscounted.

4.3. Results

Table 1 presents the TSLCC estimates for the three cases mentioned above. The costs are broken down into five major cost components: development and evaluation (D&E), transportation, first and second repository, MRS Facility, and benefit payments. The D&E cost component covers all of the siting, preliminary design, development, testing, regulatory compliance, and institutional activities for the program. This category also includes the cost of program administration by the federal government and the fees charged by the NRC for licensing. The transportation component includes the capital and operating costs of providing the transportation

Table 1. **Total system life-cycle cost estimates**[a]

Billions of 1988 dollars

Cost category	Single repositories No-new-orders	Two repositories No-new-orders	Two repositories Upper reference
D&E	11.5	15.0	15.1
Transportation	2.8	2.7	2.7
First repository	8.7	7.0	7.0
Second repository	n.a.	6.6	7.3
MRS Facility	1.9	1.6	1.6
Benefits payments	0.7	0.8	0.8
Total-system cost[b]	25.6	33.6	34.6

a) Includes historical costs since 1983.
b) Columns may not add to totals due to independent rounding.

system. The repository component covers the engineering, construction, operation, closure and decommissioning of the surface facility, packaging facility, and underground repository. Similarly, the MRS component covers the engineering, construction, operation, and decommissioning of the MRS Facility. The final cost component consists of the benefit payments to the states or affected indian tribes hosting the repository or MRS Facility.

Among the cost components provided in Table 1, the repository component corresponds to the packaging and disposal costs discussed in the main text. As a reference estimate for an international comparison, the cost for a single repository with a no-new-orders projection is estimated at $8.7 billion.

Table 2 presents the D&E cost for a single repository system, broken down into repository D&E costs and other D&E costs. Table 3 provides a breakdown of costs for the repository surface and underground costs by phases of the repository development. These phases correspond to the time schedule of Section 3.4: engineering and construction, 1996-2009; waste emplacement, 2010-2042; the caretaker phase, 2043-2059; closure and decommissioning, 2060-2075.

As shown in Table 2, the cost for first repository D&E is estimated at US$6 746 million. This consists of $847 million for site screening and US$5 899 million for site evaluation. The total site investigation cost is approximately 80 per cent ($6 746 million versus $8 737 million) of the cost of the surface facility and underground repository in the U.S. program.

Table 2. **Development and evaluation cost estimates**[a]

D&E Cost category	Millions of 1988 dollars
Repository D&E Costs	
Systems	449
Waste package	374
Site	1220
Repository	756
Regulatory/Institutional	548
Exploratory shaft facility	568
Test facilities	205
Land acquisition	4
Project management	926
Financial/Technical assistance	803
Other repository	893
Total repository	6746
Other D&E costs[b]	4762
Total D&E costs	11508

a) Include costs for single repository, no-new-orders case and historical costs since 1983.
b) Includes D&E costs for transportation, systems integration, MRS Facility, NRC fees, and government administration.

Table 3. **Repository cost estimates**
Millions of 1988 dollars

Cost Category	Phases				Total[a]
	Engineering and construction	Operations		Closure and decommissioning	
		Emplacement	Caretaker		
Management and integration	275	34	17	23	349
Site preparation	178	124	10	40	351
Waste package	n.a.	1 777	6	n.a.	1 784
Surface facilities	444	2 302	136	80	2 962
Shafts and ramps	88	23	12	5	128
Underground service systems	105	1 002	129	181	1 417
Underground excavations	86	1 458	32	168	1 745
Total[a]	1 177	6 720	343	498	8 737

a) Columns and rows may not add up to totals due to independent rounding.

4.4. Contingencies

The repository cost estimates incorporate contingency factors on an account-specific basis by phase of repository development. The composite totals of the account-specific contingencies added to the repository estimates are approximately 26 per cent (or $1 810 million) for the single repository with a no-new-orders spent-fuel projection. These contingencies are meant to account for complications such as market fluctuations, unforeseen technical problems and incomplete design specifications. Examples of account-specific contingency factors for the engineering and construction phase are contained in Table 4.

Table 4. **Repository contingency allowances**
During the engineering and construction phases

Site preparation	On-site	20%-30%
	Off site	25%-30%
	Monuments	25%
Site facilities	Waste handling facility	30%-40%
	Balance of plant	25%-30%
	Surface shaft facilities	35%-44%
Shafts/Ramps – Underground		44%-49%

5. Specific results

The packaging and disposal cost given above, $8.7 billion, corresponds to $90.8/kgU or $0.09 M/m^3 of waste or $0.38 M/TWh. It should be noted that the figure for electricity generation takes into account only the electricity from the spent fuel of commercial nuclear power plants. All these figures are in constant 1988 dollars, undiscounted.

6. Financing system

The financing system for the U.S. waste management program was established as part of the Nuclear Waste Policy Act (NWPA), which was signed into law on January 7, 1983.

The NWPA authorised the Secretary of Energy (the "Secretary") to enter into contracts with owners and generators of high-level waste for the transportation and disposal of spent fuel. The fee of 1.0 mill ($0.001) per kilowatt hour (kWh) for electricity generated by spent fuel or high-level waste after April 7, 1983 was established. The interpretation of "electricity generated" has changed twice since 1983. The 1.0 mill per kWh is now based on net electricity generated and sold to account for transmission and distribution losses. A separate one-time fee for spent fuel generated before April 7, 1983 was also levied. The utilities were given several options for repayment of the one-time fee.

The NWPA also required that if the defense waste used the same repository as the civilian waste, the DOE's Defense Program would pay the full share of the cost required for its waste disposal. There is currently no contract for the payment of waste to be disposed of from the West Valley Demonstration Project.

A separate fund in the Treasury of the United States known as the Nuclear Waste Fund, has been established. The Secretary is required to assess annually whether the collection of the fee will provide sufficient revenues to cover the costs of the program. The Secretary is required to recommend for congressional approval an adjustment to the fee, if it is found to be insufficient.

As of fiscal year (FY) 1990 (*i.e.*, year ending September 30, 1990), approximately $4.5 billion (current year dollars) had been paid by the utilities into the Nuclear Waste Fund. From the inception of the programme in 1983 through FY 1990, approximately $2.7 billion has been spent from the fund.

7. Fee assessment

Six assessments of the fee have been performed by the DOE to date and have determined that the collection of 1.0 mill per kWh fee will produce revenues sufficient to cover the costs of the program. The estimated fund balance at the end of the program in the most recent analysis is estimated to be a surplus of 3 billion constant 1988 dollars. The most recent analysis based its findings on a single-repository system, a base-case inflation rate of 4 per cent and a real interest rate of 3 per cent.

The DOE has recognised in previous fee adequacy reports that the fee will probably need to be increased at some time in the future. Several factors indicate this. First, since the fee was established in 1982, the purchasing power of that fee has decreased with inflation. Second, a Federal Court decision requiring a change in the way that the fee is calculated (to compensate for transmission and distribution losses) will reduce the revenues received. Third, with the scenario of no new reactors being ordered, the estimated amount of fees to be received has been reduced significantly since the passage of NWPA. Fourth, a recent report from the Inspector General concluded that the DOE was at risk in not receiving the fees from the utilities who selected a deferred payment option for repayment of the one-time fee. Fifth, program cost estimates are higher than previously estimated.

There are several reasons why a fee increase at this time is not clearly indicated. First, inflation rates for the life of the program should be conservatively estimated in order to avoid over-collection of the fees. Second, increased revenues cannot be ruled out because of the continuing concern over global warming and the possibility of reactor life extension. Third, program costs could vary by $8 billion depending upon the number of repositories assumed. Fourth, with the recent announcement of a delay in the opening of the repository to the year 2010, many utilities are concerned about the additional cost of at-reactor storage during the delay years.

References

"Nuclear Waste Policy Act of 1982", Pub. L. No. 97-425, January 7, 1983.

"Nuclear Waste Policy Amendments Act of 1987", Pub. L. No. 100-203, December 1987.

U.S. Department of Energy, Office of Civilian Radioactive Waste Management, *Site Characterization Plan*, (DOE/RW-0198), December 1988.

U.S. Department of Energy, Office of Civilian Radioactive Waste Management, *Report to Congress on Reassessment of the Civilian Radioactive Waste Management Program*, (DOE/RW-0247), November 1989.

U.S. Department of Energy, Office of Civilian Radioactive Waste Management, *Preliminary Estimates of the Restructured Program: An Addendum to the May 1989 Analysis of the Total-System Life Cycle Cost for the Civilian Radioactive Waste Management Program*, (DOE/RW-0295P), December 1990.

U.S. Department of Energy, Office of Civilian Radioactive Waste Management, *Nuclear Waste Fund Fee Adequacy: An Assessment*, (DOE/RW-0291P), November 1990.

Annex 2

List of abbreviations and glossary of terms*

Actinide:

An element with an atomic number from 89 to 103, inclusive. All are radioactive.

Activity:

The number of spontaneous nuclear disintegrations occurring in a given quantity of a radionuclide per unit of time. It is normally expressed in becquerels (Bq) or in curies (Ci).

AGR (Advanced-Gas-Cooled Reactor)

A gas-cooled reactor with stainless steel-clad slightly enriched uranium dioxide fuel elements; cooled by carbon dioxide.

Alpha-bearing waste:

Waste containing one or more alpha-emitting radionuclides, usually actinides, in quantities above acceptable limits for controlled release. The limits are established by the national regulatory body.

Backfill:

An act of refilling the excavated portions of a repository or of a borehole after waste has been emplaced.

Basalt:

A dark-coloured igneous rock, commonly extrusive, composed primarily of calcic plagioclase and pyroxene; the fine-grained equivalent of gabbro.

Bedded salt:

A salt formation in which the salt is roughly horizontal, laterally extensive and relatively thin in the vertical direction.

Bentonite:

A soft plastic light-coloured clay. Bentonite is ideally suited for use as a buffer material for surrounding waste packages in a deep repository.

Borosilicate glass:

a) a supercooled liquid based on a random lattice of silica tetrahedra, modified with boron and other cations;
b) a glass composition used as an immobilization matrix for a radioactive waste.

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* This Annex was prepared on the basis of the IAEA documents below:
- Radioactive Waste Management Glossary, IAEA-TECDOC-264, Vienna, 1982.
- Radioactive Waste Management Glossary, Second Edition, IAEA-TECDOC-447, Vienna, 1988.

Bq (Becquerel):

The SI unit of radioactivity, equivalent to 1 disintegration per second (approx. 3.7×10^{-10} Ci).

Buffer material:

Any substance placed around a waste container in a repository.

Burnup:

A measure of consumption of the fissile content of reactor fuel. Units normally used for are megawatt-days per tonne of uranium (MWd/tU), or heavy metal (MWd/tHM).

BWR (Boiling-Water Reactor):

A light-water reactor in which water, used as both coolant and moderator, is allowed to boil in the core. The resulting steam can be used directly to drive a turbine.

CANDU (Canada Deuterium Uranium Reactor):

A pressurized heavy water reactor of Canadian design, which uses natural uranium as a fuel and heavy water as a moderator and coolant.

Canister:

A closed or sealed container for spent nuclear fuel or other radioactive waste material. A canister may be placed in a cask for transport or storage, or in an overpack for disposal.

Cask:

A massive outer container to transport and/or store irradiated nuclear fuel and other radioactive materials. A ''cask'' is not normally used for final disposal.

CEC:

Commission of the European Communities.

Clay:

Minerals that are essentially hydrous aluminium silicates or occasionally hydrous magnesium silicates, with sodium, calcium, potassium and magnesium cations. Also denotes a natural material with plastic properties which is essentially a composition of fine to very fine clay particles. Clays differ greatly mineralogically and chemically and consequently in their physical properties.

Conditioning:

Those operations that transform waste into a form suitable for transport and/or storage and/or disposal. ''Packaging'' is a sub-concept of ''conditioning''.

Container:

A generic word, used sometimes instead of canister, cask and overpack.

Deep geologic repository:

A repository constructed, usually in consolidated rock, at a depth of several hundred metres or more in a continental formation.

Decommissioning:

The work required for the planned permanent retirement of a nuclear facility from active service.

Encapsulate:

The act of immobilizing radioactive waste such as spent fuel in a matrix within a canister. Thus simple enclosure is not ''encapsulation''.

Discounting:

A procedure to convert the value of money earned or spent in the future to a present value. If one had $A and it could be invested to earn interest at a real money rate ''r'' per annum, in ''t'' years it would increase to become $A $(1 + r)^t$. A sum of $B earned or spent in t years time can be said to have a present value of $B/$(1 + r)^t$. The ''r'' is entitled a ''discount rate''.

Disposal:

The emplacement of waste materials in a repository, or at a given location, without the intention of retrieval. Disposal also covers the approved direct discharge of wastes into the environment, with subsequent dispersion.

Dome salt:

A local geologic formation of salt in which the salt thickness is greater vertically than laterally.

Granite:

Broadly applied, any holocrystalline quartz-bearing plutonic rock.

Emplacement:

Placing the waste in its location for storage or disposal.

Fission product:

A nuclide produced either by fission or by the radioactive decay of the nuclides formed by fission.

GCR (Gas-Cooled Reactor):

A reactor in which a gas such as air, carbon dioxide or helium is used as a coolant.

High-Level Waste:

The highly radioactive waste material that results from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid waste derived from the liquid and which contains a combination of TRU waste and fission products in such concentration as to require long-term isolation.

HM (Heavy Metal):

All the isotopes of Th, U, Np, Pu, Am and Cm.

Host rock:

A geological formation in which a repository is located.

IAEA:

International Atomic Energy Agency.

Igneous rock:

Rock formed by solidification of hot mobile material formed within the upper mantle of the earth, termed magma.

Interim storage:

A storage operation for which:

a) monitoring and human control are provided; and
b) subsequent action involving treatment, transportation, and final disposition is expected.

Intermediate-Level Waste (or medium-level waste):

Waste of a lower activity level and heat output than high-level waste, but which still requires shielding during handling and transportation.

Low-Level Waste:

Waste which, because of its radionuclide content, does not require shielding during normal handling and transportation. (See "alpha-bearing waste" and "high-level waste" for other possible limitations).

LWR (Light Water Reactor):

A nuclear reactor that uses ordinary water as both a moderator and a coolant and utilises slightly enriched uranium-235 fuel. There are two commercial LWR types: the BWR and the PWR.

Magnox reactor:

A gas-cooled reactor cooled by carbon dioxide; using Magnox alloy (a magnesium alloy with low aluminium content) as a cladding material for metallic natural uranium fuel.

MOX fuel (mixed oxide fuel):

Fuel which is an intimate mixture of uranium and plutonium oxides.

MWe (Megawatt electric):

10^6 watt electric.

MWd/tU (Megawatt days per tonne of uranium):

A unit of burnup.

MWd/tHM (Megawatt days per tonne of heavy metal):

A unit of burnup.

NEA:

Nuclear Energy Agency.

OECD:

Organisation for Economic Co-operation and Development.

Overpack (noun):

A secondary (external) container over a canister, or canisters, for additional containment of the nuclear waste in a geologic repository.

Overpack (verb):

The act of placing a secondary container (overpack) over the canister containing the waste.

Pa (Pascal):

The SI unit of pressure. 1 Pa = 1 N/m^2. 1 atm = 101325 Pa.

Package (verb):

The act of preparing and/or enclosing the waste in the form appropriate for waste disposal. "Packaging" is a generic word and includes "encapsulation" and "overpacking". "Simple emplacement of waste in a canister" is also included in "packaging".

PWR (Pressurized-Water Reactor):

A light-water reactor in which heat is transferred from the core to a heat exchanger via water kept under high pressure, so that high temperatures can be maintained in the primary system without boiling the water. Steam is generated in a secondary circuit.

Radioactivity:

The property of certain nuclides of spontaneously emitting particles or gamma radiation, or of emitting X-radiation following orbital electron capture, or of undergoing spontaneous fission.

Repository:

A facility or designed site for storage or disposal of radioactive wastes.

Reprocessing:

A generic term for the chemical and mechanical processes applied to fuel elements discharged from a nuclear reactor. The purpose is to remove fission products and recover fissile (uranium-233, uranium-235, plutonium-239), fertile (thorium-232, uranium-238) and other valuable material.

Reprocessing waste*:

High-level vitrified waste and alpha-bearing waste from reprocessing.

Retrievability:

The capability to remove waste from where it has been stored.

Safeguards, IAEA:

A system of measures within the framework of the international non-proliferation policy entrusted to the IAEA in its Statute and by the Non-Proliferation Treaty (NPT). The objectives of the IAEA safeguards are to provide timely detection of diversion of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection. The IAEA applies its safeguards only to peaceful nuclear activities.

Safeguards, domestic:

Measures employed by a nation to prevent or detect the diversion of nuclear material and to protect against the sabotage of facilities. The safeguards employed by a nation (domestic safeguards) should not be confused with the IAEA safeguards (international safeguards).

Salt:

A geological formation containing mainly halite (NaCl) with smaller inclusion of other minerals. Salt formations occur as bedded or domal deposits.

Schist:

A metamorphic banded rock with a predominance of bedded mica minerals.

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* The definition is applicable only for this report.

Spent fuel:

Irradiated fuel units not intended for further reactor service.

Thermal loading:

The quantity of heat-generating materials placed in a given area or volume; units are power per area or volume respectively.

Tuff:

One of a series of pyroclastic rocks composed of consolidated ash from fragmental volcanic material blown into the atmosphere by volcanic activity.

TWh (Terawatt-hour):

The unit for electricity. 1 trillion (10^{12}) watt-hours.

Vitrification:

Any process of converting materials into a glass or glass-like form.

Vitrified waste:

Waste immobilized into a glass or glass-like matrix.

Waste management:

All activities, administrative and operational, that are involved in the handling, treatment, conditioning, transportation, storage and disposal of waste.

Waste package:

The waste form and any container(s) as prepared for the handling, transport, treatment, conditioning, storage and disposal of waste.

Water table:

a) the upper surface of the groundwater;
b) the upper surface of a zone of groundwater saturation.

Annex 3

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* Mr. Knecht attended only the first Expert Group meeting and no representative of Switzerland attended the other meetings. However, Dr. McCombie and Dr. McKinley from NAGRA contributed information and comments by mail.

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