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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NUCLEAR ENERGY AGENCY
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 DANS DES FORMATIONS GÉOLOGIQUES
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].

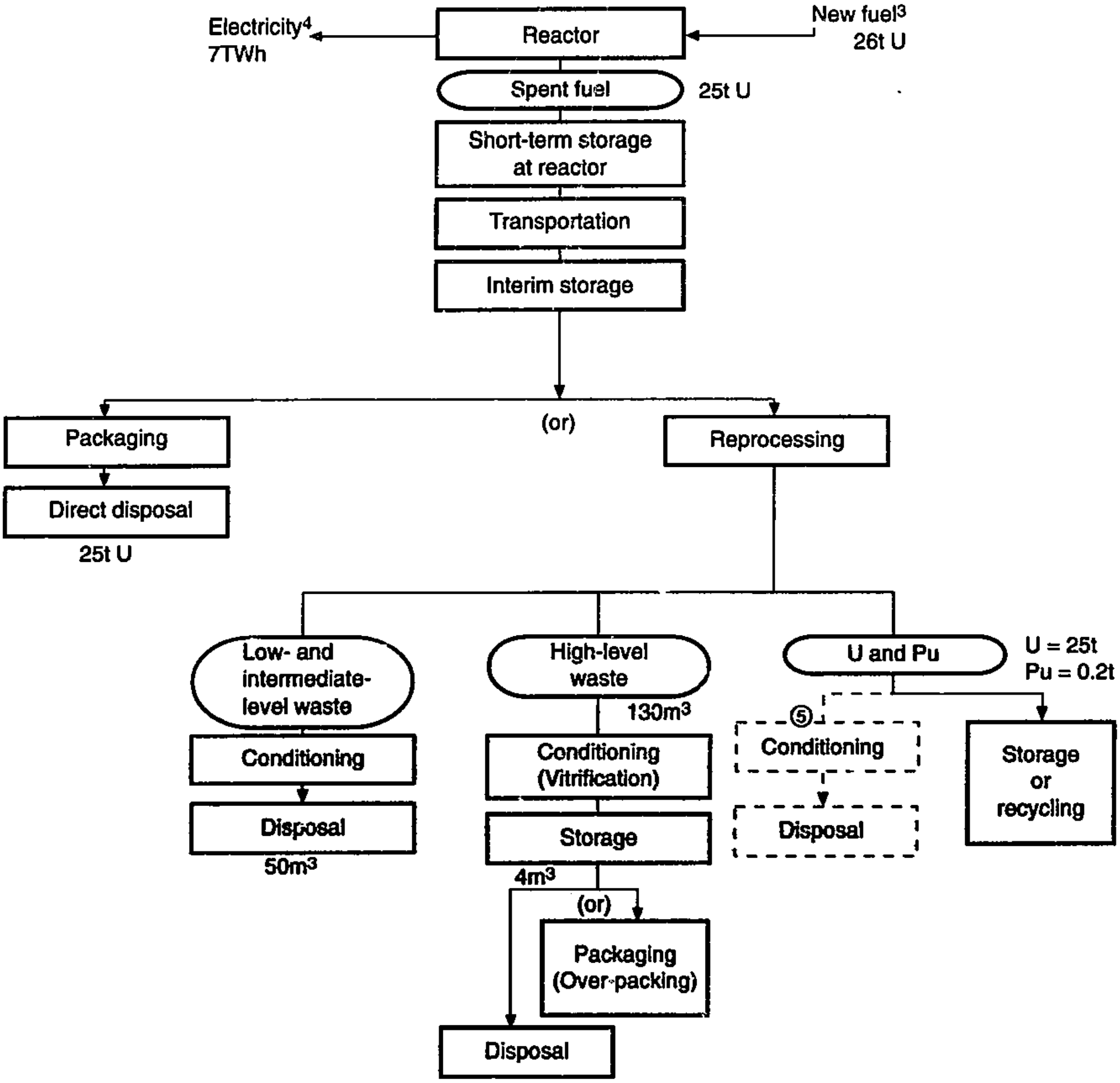
In the remainder of this chapter, an overview is given of the main components of the spent fuel management system, and the characteristics of the spent fuel and the wastes to be considered are described. A more detailed explanation of the final disposal stage, including packaging as needed, is given 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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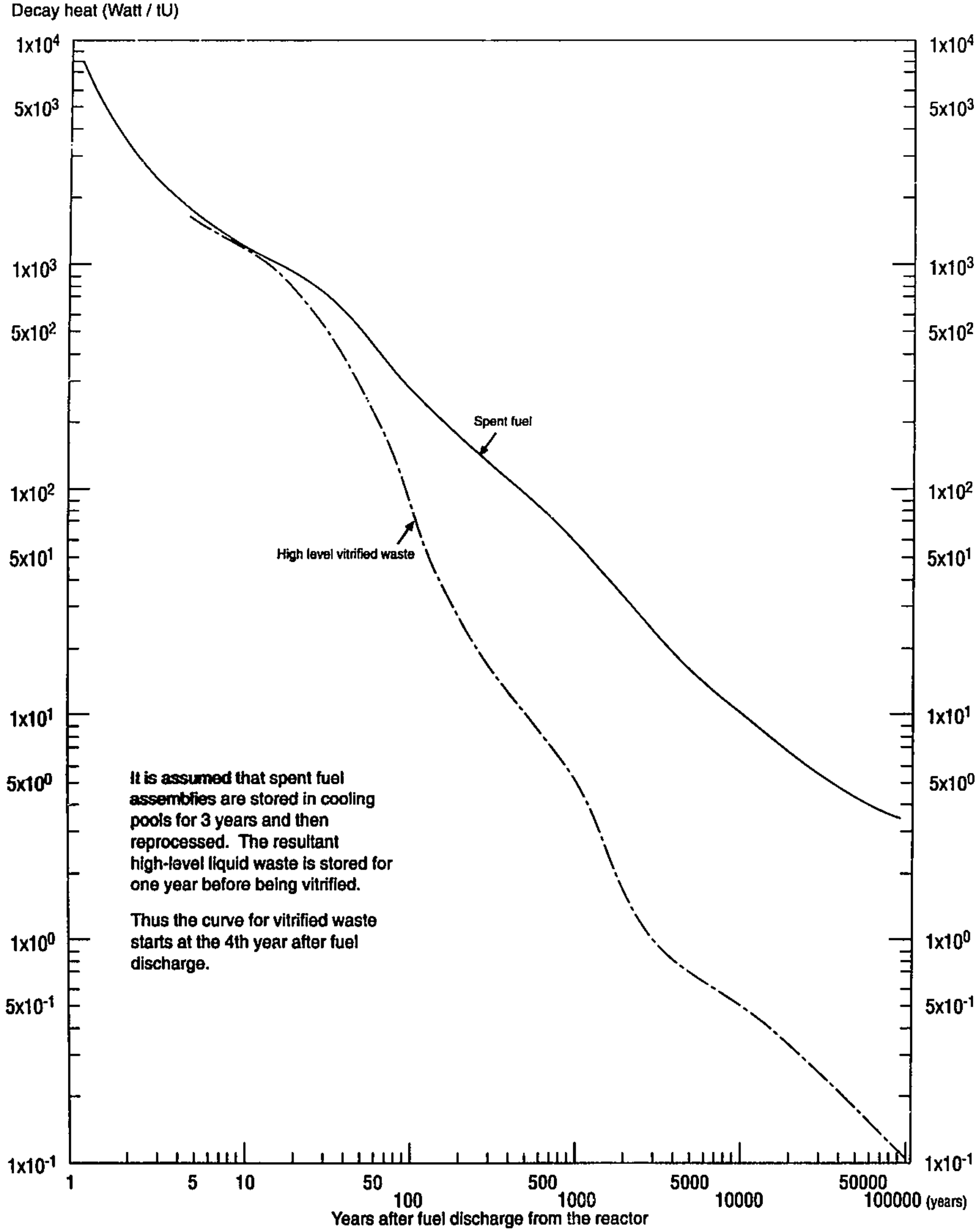
* In this report, burnup is consistently given in MWd/tU, although MWd/tHM (tonne of heavy metal) is more precise.

** 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**

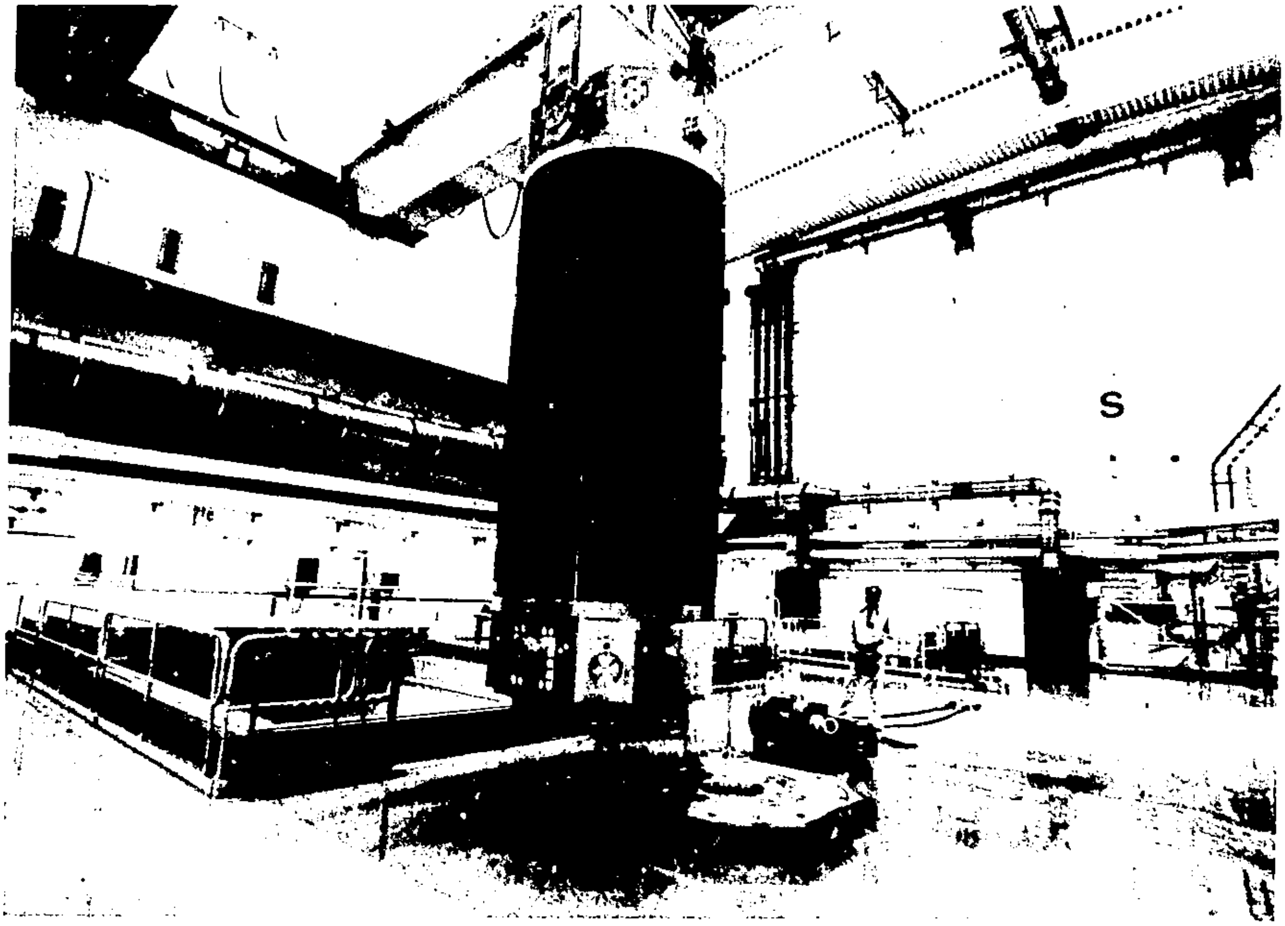


It is assumed that spent fuel assemblies are stored in cooling pools for 3 years and then reprocessed. The resultant high-level liquid waste is stored for one year before being vitrified.

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.

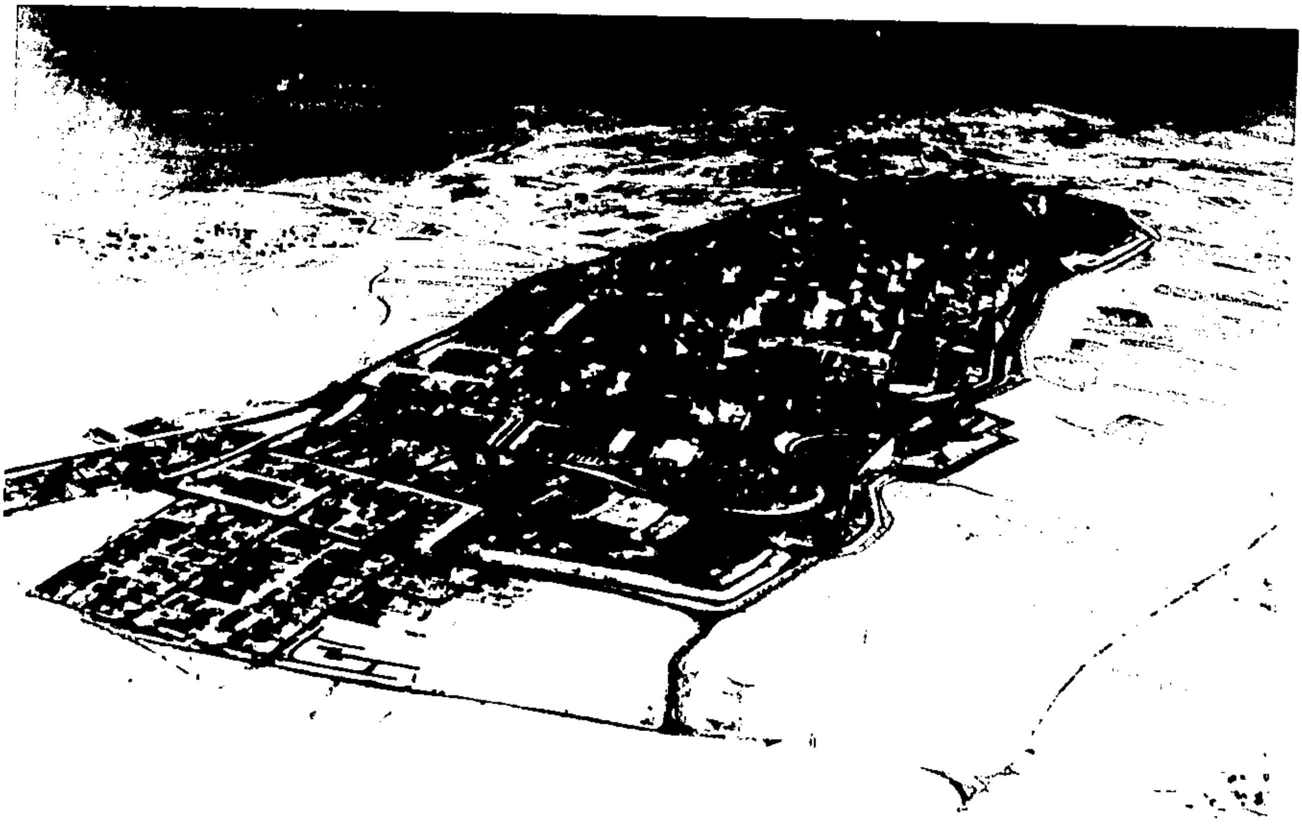
In cases where the cooling pond at the reactor site has sufficient capacity or where the pond or dry storage capacity could be reasonably expanded, interim storage could take place at the reactor. In this case, the spent fuel could be kept in interim storage at the reactor site for several decades.

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

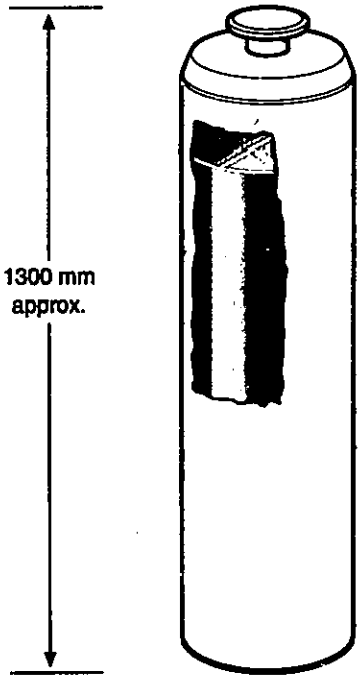


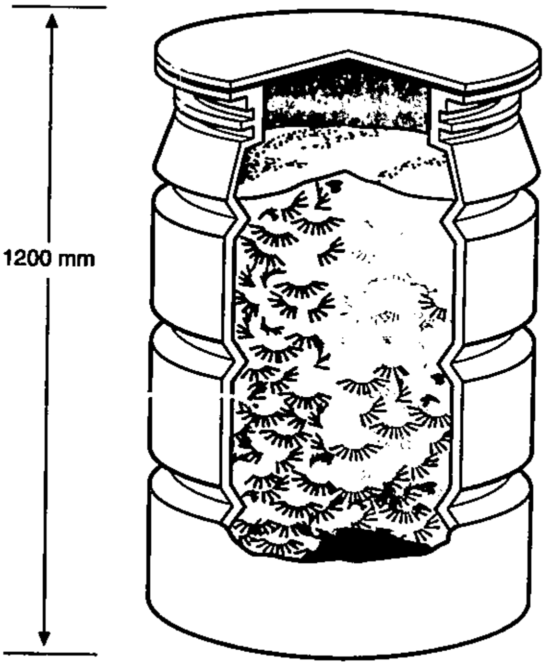
Table 2.2. **Characteristics of typical high-level vitrified waste**[a]

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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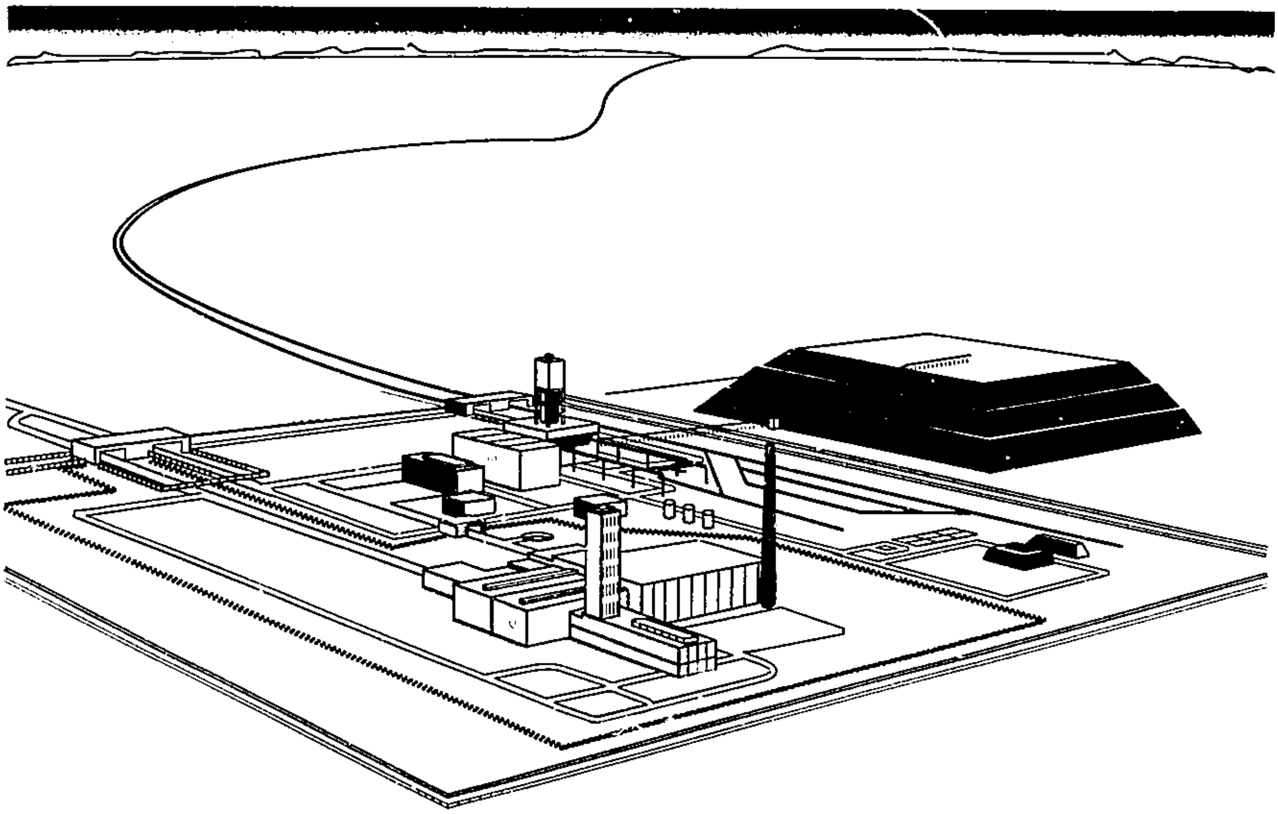
* Hereafter, the word "container" is a generic word for disposal purposes, and includes "canister" and "overpack". A canister is a closed or sealed container for spent fuel or reprocessing waste. An overpack is a secondary external containment and/or shielding for radioactive waste packaged in a canister (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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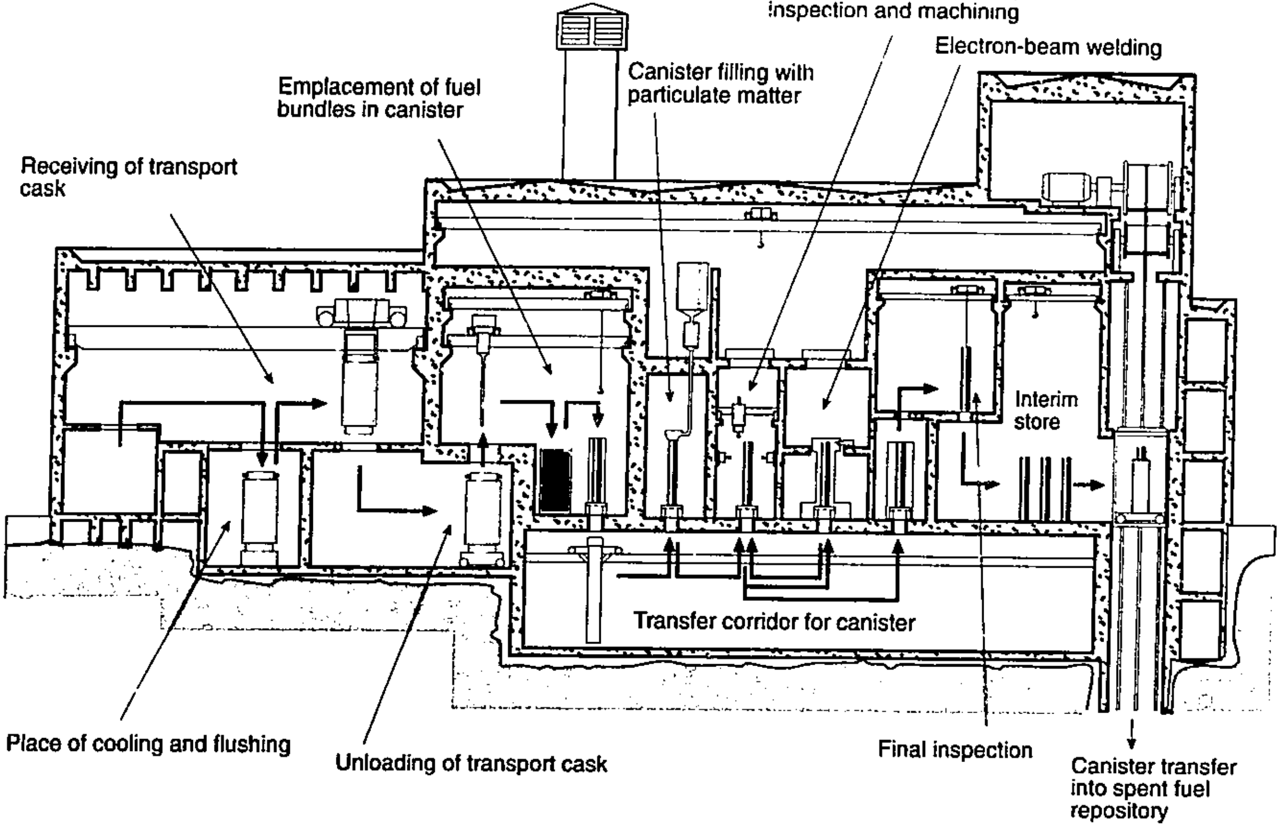
* Safeguards are measures to prevent or detect the diversion of nuclear material and to protect against the sabotage of facilities. The safeguards employed by a nation (domestic safeguards), which sometimes cover measures for physical protection, may be different from the IAEA safeguards (international 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).

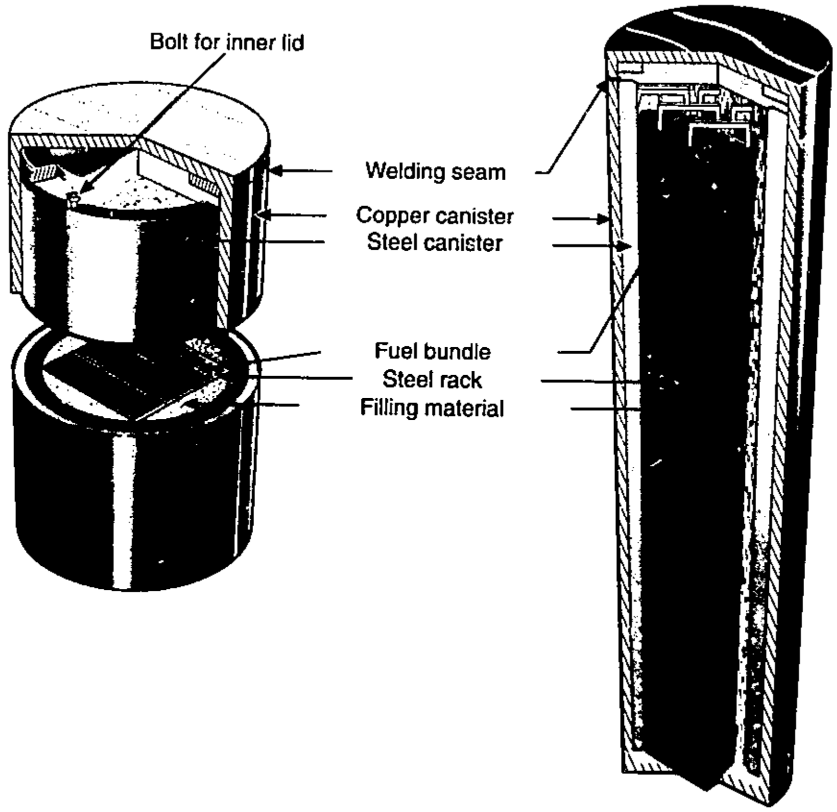
3.2.2.1. Canada

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.

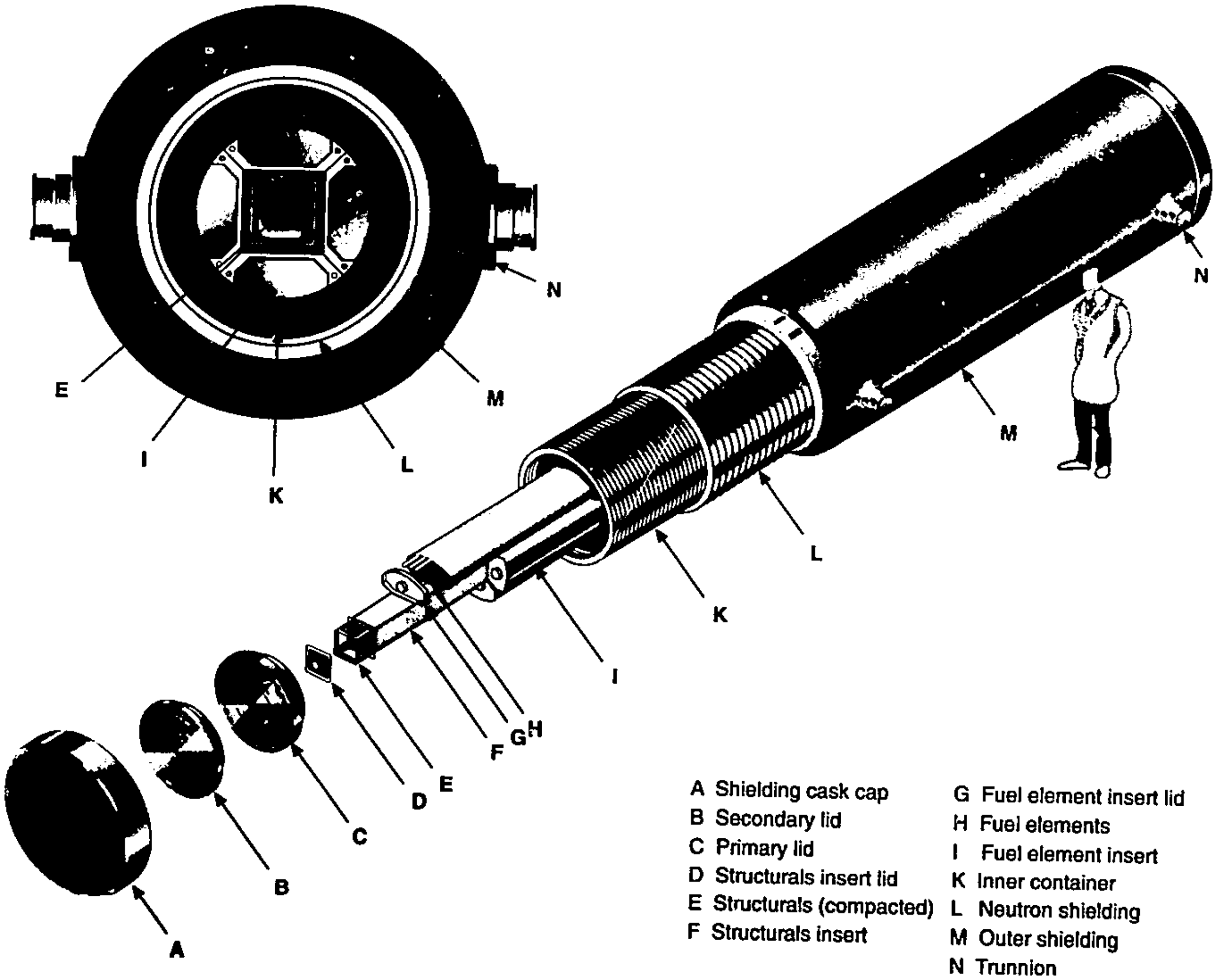
The inner steel container will make the container self-supporting, and the outer copper will give the container a very long service life (corrosion resistance).

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**



A Shielding cask cap
B Secondary lid
C Primary lid
D Structurals insert lid
E Structurals (compacted)
F Structurals insert
G Fuel element insert lid
H Fuel elements
I Fuel element insert
K Inner container
L Neutron shielding
M Outer shielding
N Trunnion

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

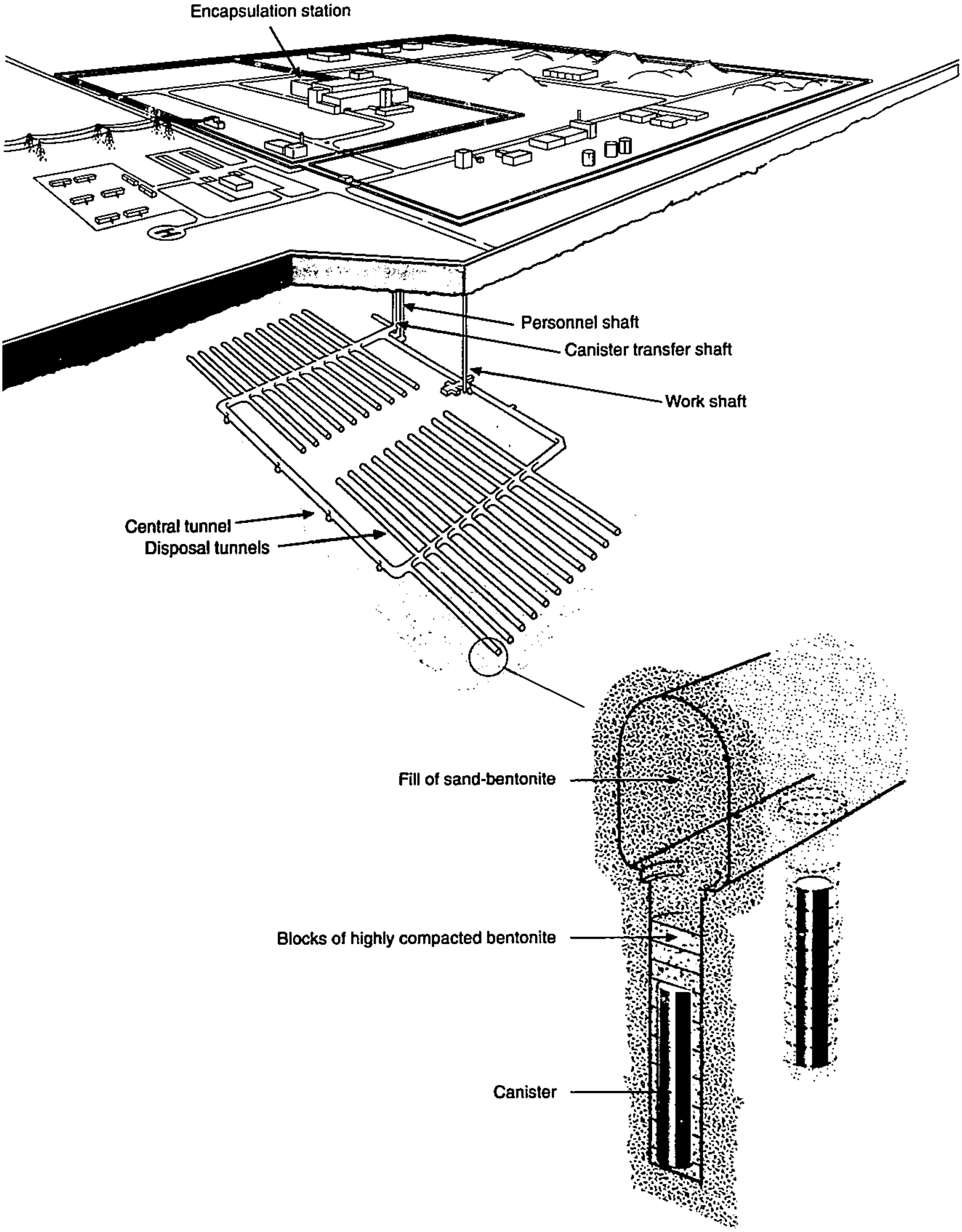
The preliminary conceptual design performed in Spain assumes a repository built in granite rock at a depth of about 500 m. The repository consists of parallel disposal galleries, with corresponding transport tunnels and service areas. Access to the repository will be via a ramp.

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.

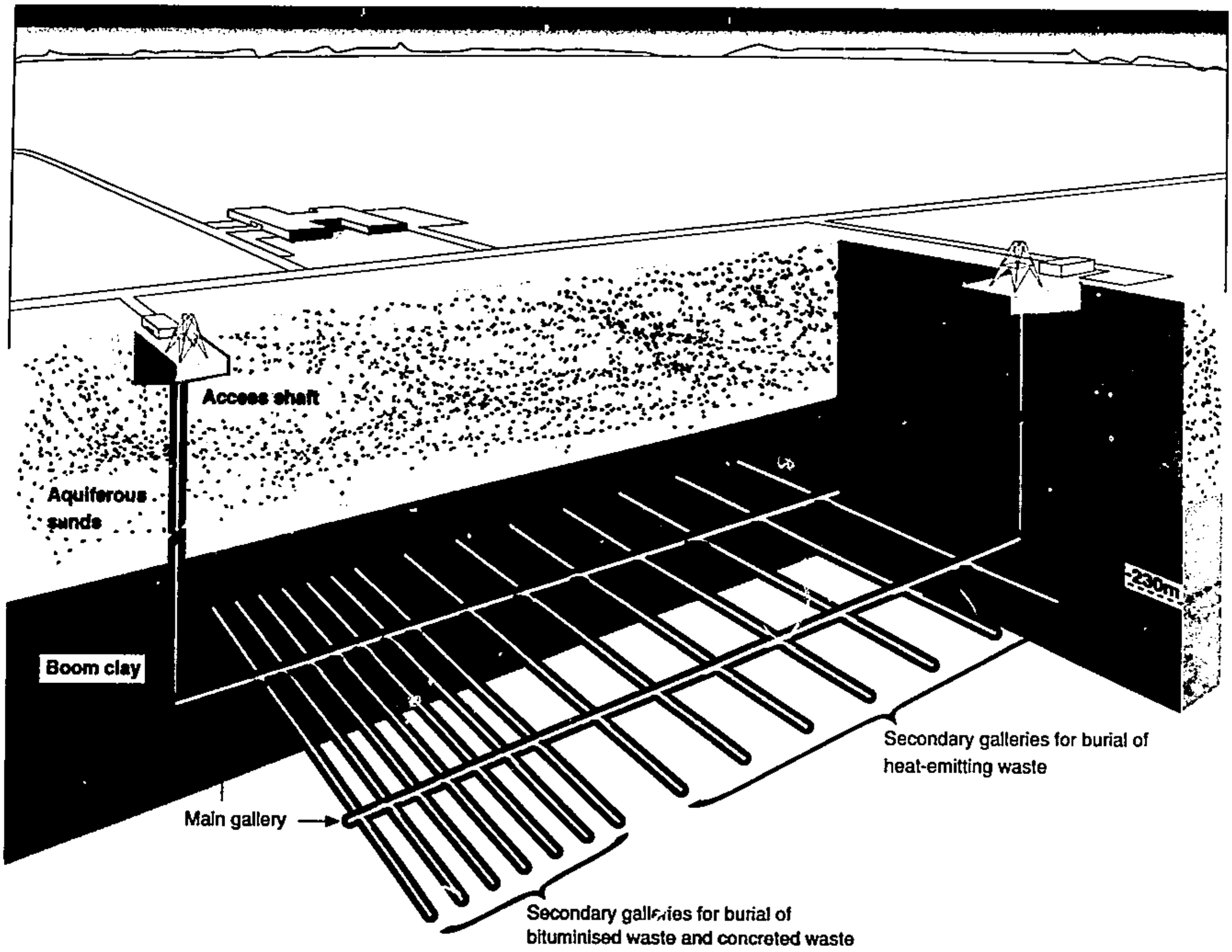
3.3.3. Repositories in clay

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.

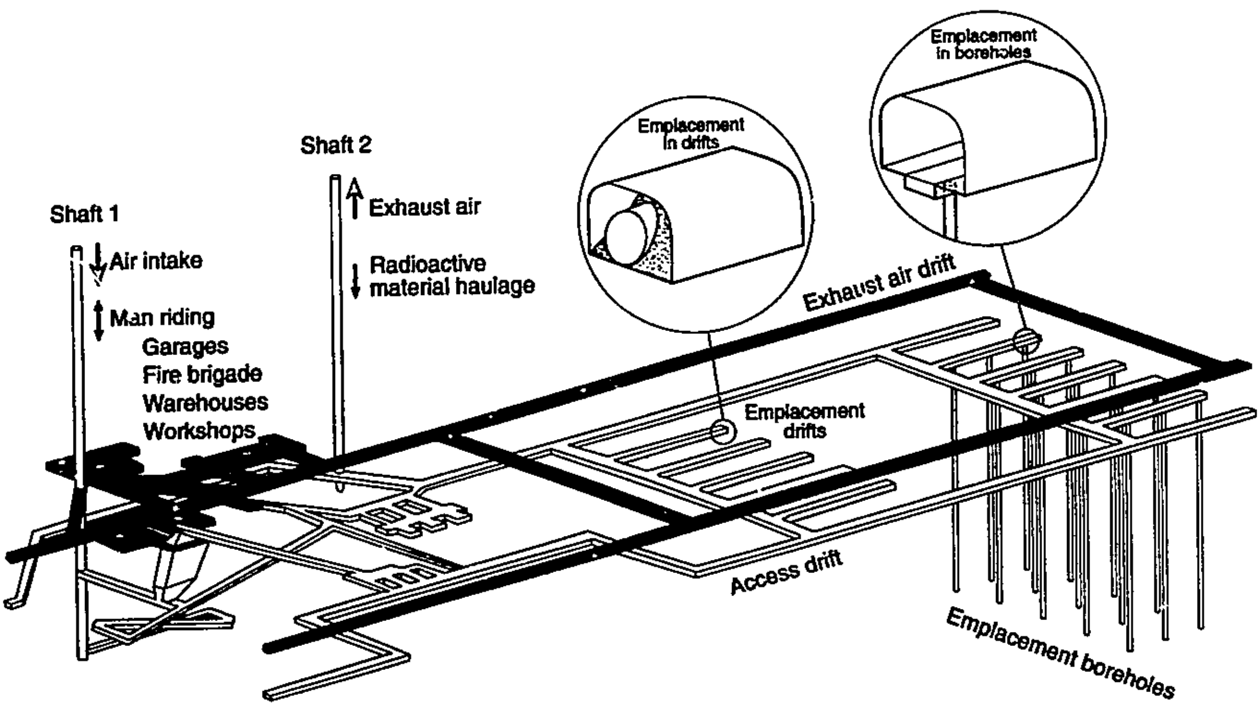
3.3.4. *Repositories in salt*

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

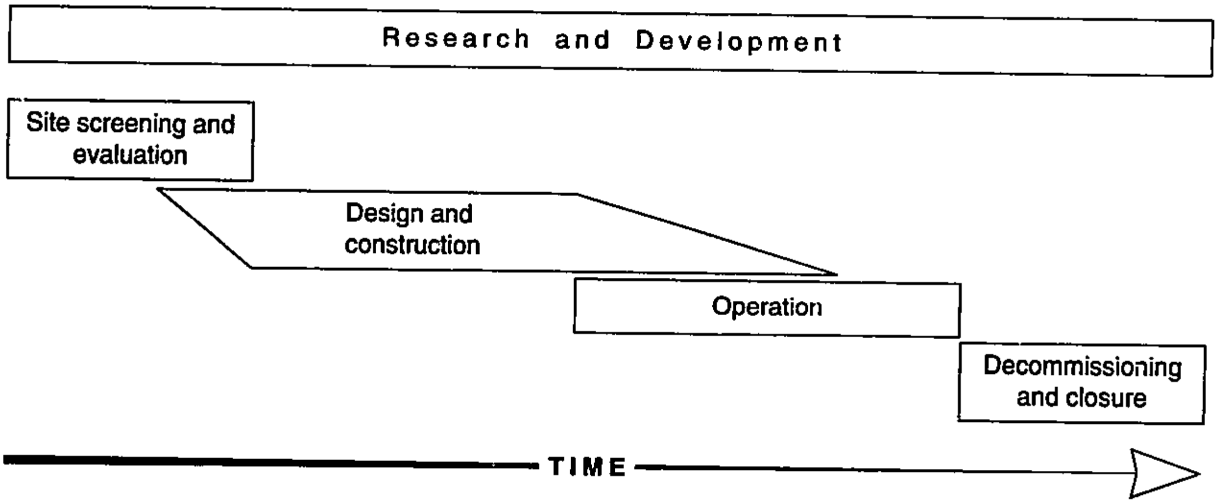
COST COMPONENTS

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).

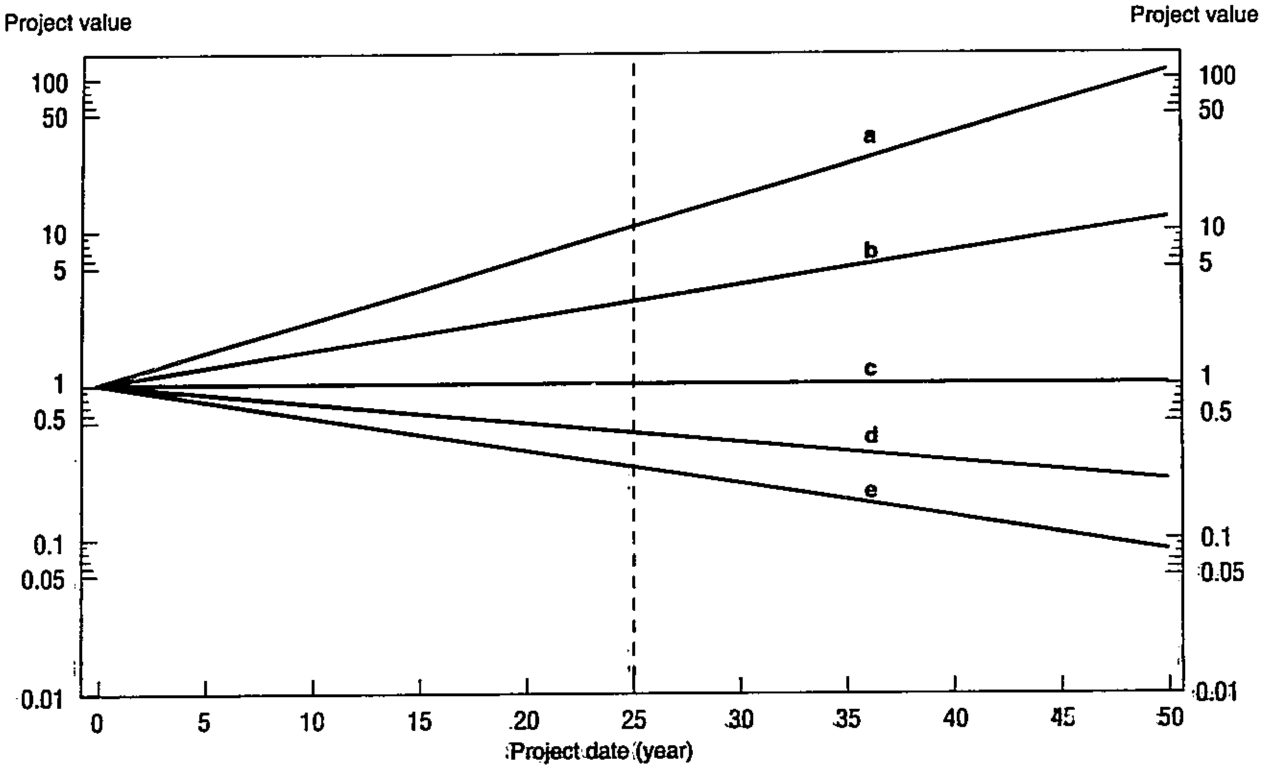
c) Calculate the levelised unit costs. That is, calculate the net present value of services, such as waste disposal and electricity generated, according to the methodology described in a) and b), and then obtain the levelised unit costs by dividing the present value of the costs by the present value 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.

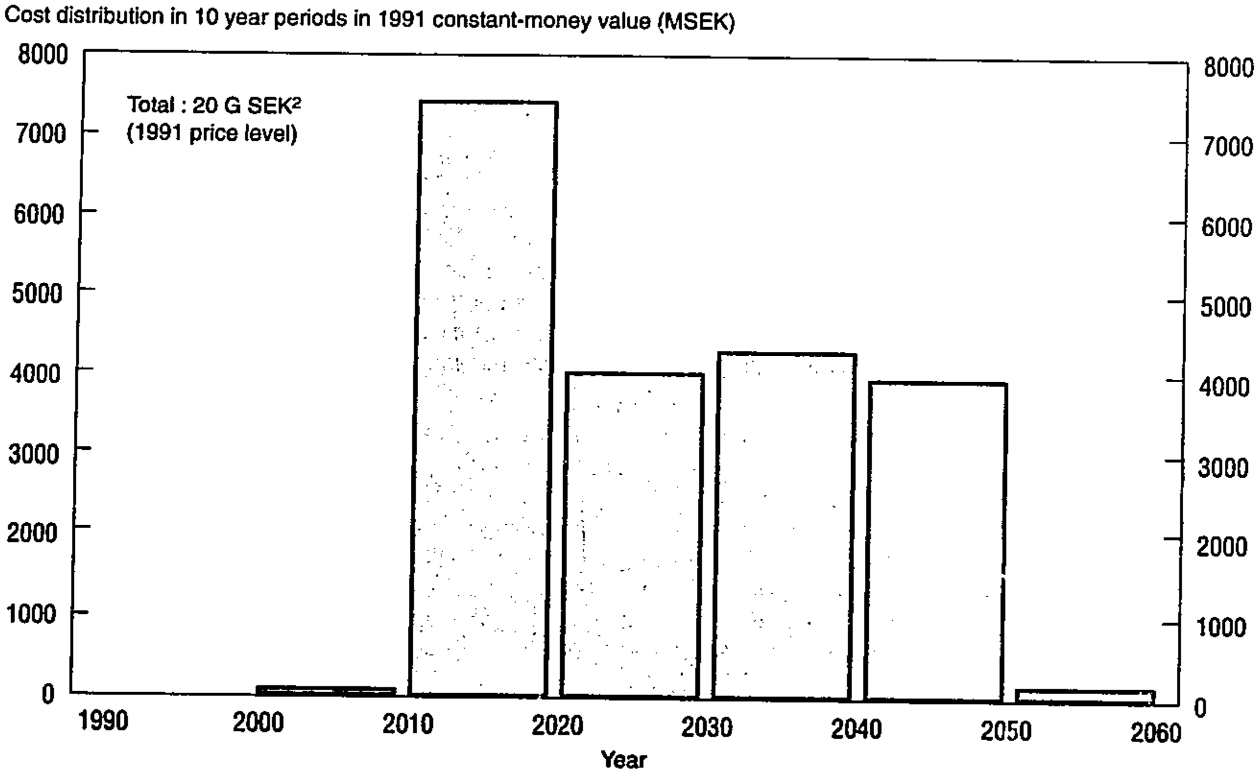
Table 5.1. **Example of the effect of inflation and real interest rate assumptions on the results of cost calculations**

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] (m^3)	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 m^3)	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] (m^3)	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 m^3)	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 m^3 of which is hulls and caps; and some 250 m^3 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 m^3 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	k\$/m^3	\$/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 (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 (\$/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	k\$/m^3	\$/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.

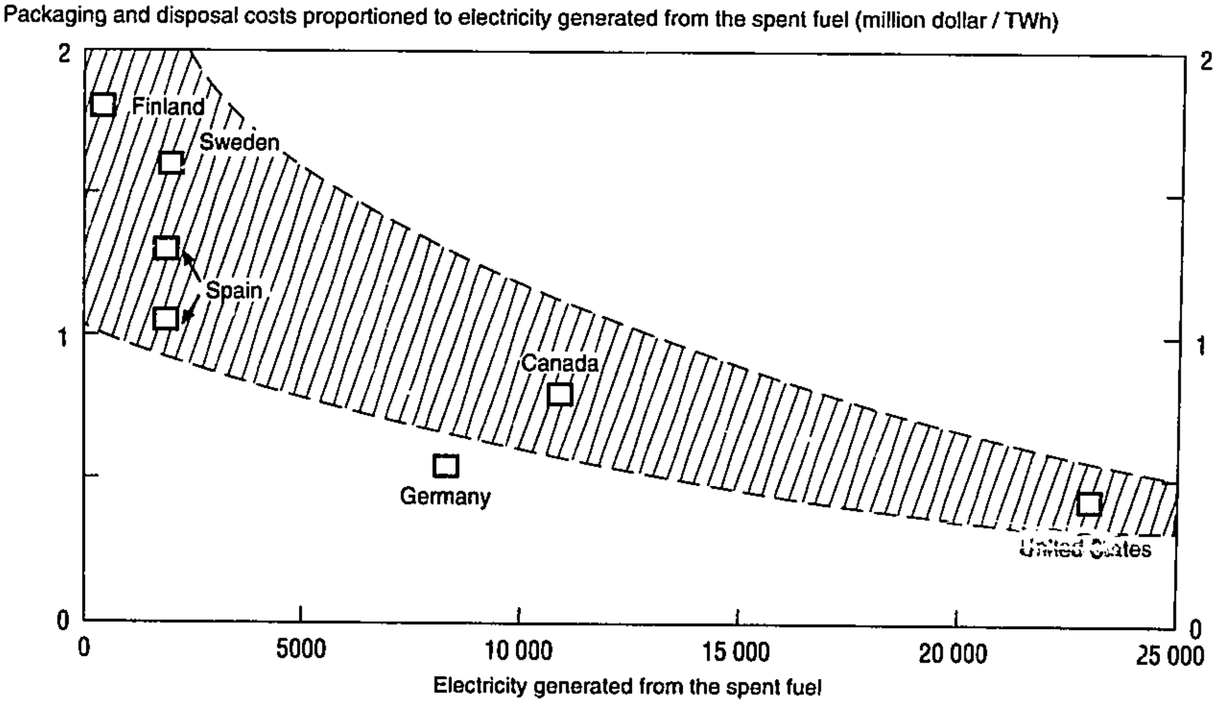
The total costs reported for the packaging and final disposal of spent fuel vary between $ 0.76 billion for Finland and $ 10.0 billion for the US. The most important factor in this large variation is, of course, the amount of fuel to be disposed of.

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.

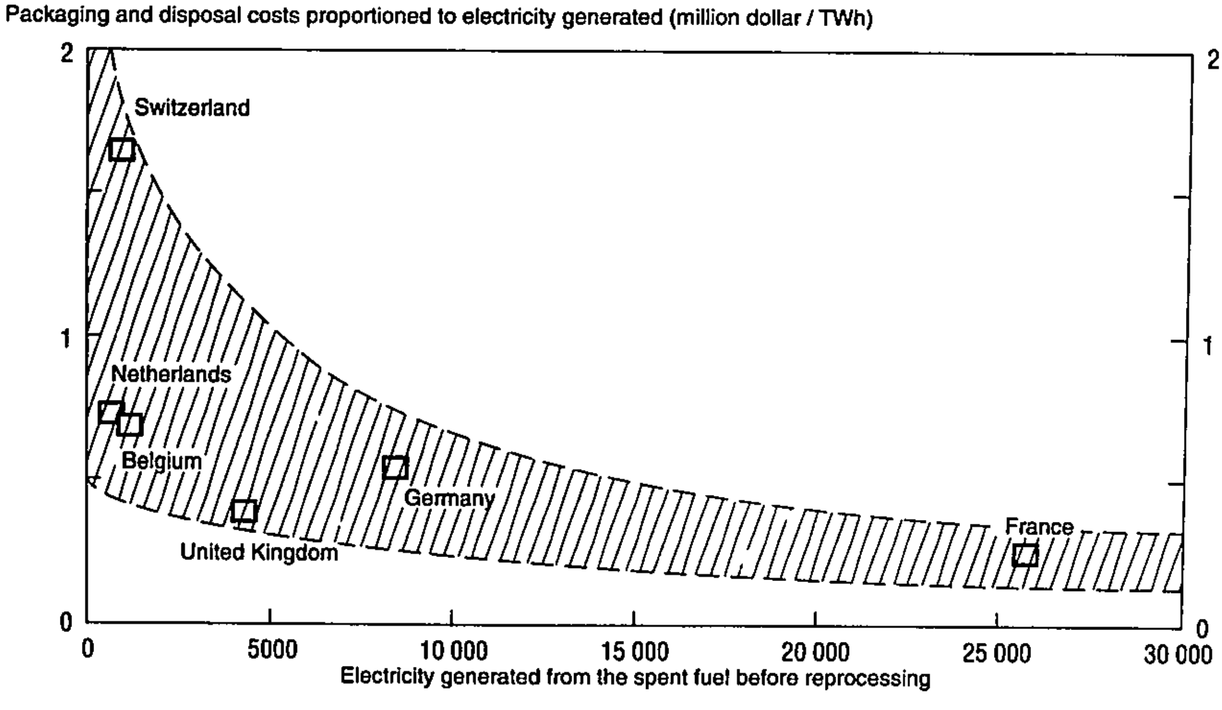
In column [D], only the cost for underground work (excavation, disposal, backfilling and sealing) is normalized to the total volume of rock excavated. In the case of crystalline rock, the results show the effect of scale, but also indicate that the basic costs are different in Europe and in North America. 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).