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COSTING METHODS AND FUNDING SCHEMES FOR RADIOACTIVE WASTE DISPOSAL PROGRAMMES

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IAEA NUCLEAR ENERGY SERIES No. NW-T-1.25

COSTING METHODS AND FUNDING SCHEMES FOR RADIOACTIVE WASTE DISPOSAL PROGRAMMES

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2020

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Printed by the IAEA in Austria
November 2020
STI/PUB/1900

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Costing methods and funding schemes for radioactive waste disposal programmes / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2020. | Series: IAEA nuclear energy series, ISSN 1995–7807 ; no. NW-T-1.25 | Includes bibliographical references.
Identifiers: IAEAL 20-01342 | ISBN 978–92–0–108819–2) | (paperback : alk. paper) ISBN 978–92–0–111720–5 (pdf) | ISBN 978–92–0–111820–2 (epub) | ISBN 978–92–0–111920–9
Subjects: Radioactive waste disposal. | Cost accounting. | Cost estimates | Risk management
Classification: UDC | STI/PUB/1900

FOREWORD

The IAEA's statutory role is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Among other functions, the Agency is authorized to "foster the exchange of scientific and technical information on peaceful uses of atomic energy". One way this is achieved is through a range of technical publications including the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series comprises publications designed to further the use of nuclear technologies in support of sustainable development, to advance nuclear science and technology, catalyse innovation and build capacity to support the existing and expanded use of nuclear power and nuclear science applications. The publications include information covering all policy, technological and management aspects of the definition and implementation of activities involving the peaceful use of nuclear technology.

The IAEA safety standards establish fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment from harmful effects of ionizing radiation.

When IAEA Nuclear Energy Series publications address safety, it is ensured that the IAEA safety standards are referred to as the current boundary conditions for the application of nuclear technology.

This publication provides Member States with information on how to develop cost estimates for a disposal programme and on how to establish adequate and reliable funding mechanisms. The information is intended to be practical, enabling Member States to set up estimates and funding schemes for their disposal programmes, and it is applicable to all waste categories and both near surface and geological disposal.

Although this publication is aimed at those involved or interested in the cost of a disposal programme, it will be of interest primarily to waste management organizations which implement a disposal programme and which need to understand the associated financial liabilities and need to establish schemes to fund the programme.

The publication contains examples and case studies from national programmes, which illustrate applied cost estimation and funding mechanisms. The figures in US dollars are to give an indication of the possible cost of aspects of the disposal programme and are not provided to compare the cost of different disposal programmes.

The IAEA is grateful to all who contributed to the drafting and review of this publication. The IAEA officers responsible for this publication were P. Van Marcke and S. Mayer of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Nuclear science and technologies are used in many applications worldwide. Electricity production in nuclear power plants is probably the best known example of the use of nuclear energy. However, nuclear applications can be found in a wide variety of sectors, such as health, food and agriculture, the environment, water resources and industry. These applications can bring great benefits to countries and their populations.

The use of nuclear science and technologies, however, also entails responsibilities which stretch beyond the safe operation of those nuclear technologies. Closed nuclear facilities need to be decommissioned, sites where radioactive ores, such as uranium, were mined need to be remediated and the waste generated by nuclear applications needs to be taken care of. As radioactive waste remains hazardous for tens to hundreds of thousands of years, its management needs to protect human health and the environment both now and in the future, without imposing an undue burden on future generations [1]. This objective is reflected in the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (Joint Convention) [2].

States thus need to establish policies and strategies for the safe management of radioactive waste and spent fuel declared as waste. The main elements of a waste management policy and strategy are set out in Ref. [3].

The last step of the long term management of radioactive waste is disposal. Disposal in near surface repositories[1] is the generally accepted solution for very low level waste (VLLW) and low level waste (LLW). Intermediate level waste (ILW) and high level waste (HLW), as well as spent fuel declared as waste, require disposal in an underground repository.

A fundamental prerequisite for implementing a sustainable waste disposal programme is the provision of financial resources to cover the costs of the programme. Insufficient financial resources can jeopardize the implementation of the disposal programme (see Section 2.1.4). Financial resources and provisions need to cover future costs and will arise after the benefits resulting from the activities have been gained. Financial liabilities are the future costs resulting from past or current activities and need to be identified and correctly assessed so that provisions are made to cover the expenditures to discharge those liabilities (see Ref. [5]).

Reliable methods for estimating the cost of the disposal programme are therefore crucial to ensure that adequate funding is available and will be maintained until the disposal programme's completion, including post-closure monitoring and institutional control. Cost estimates will also assist decision makers and project engineers in the development of the disposal concept, as they can quantify the cost impact of certain design choices. It is therefore necessary that these cost estimation methods are implemented early in the disposal programme. Establishing such reliable cost estimates and related adequate funding schemes is, however, a challenging and complex task because the disposal programmes are complex, long term undertakings that face many challenges, both scientific and technological and also economic, societal and political, and in which many stakeholders are involved. Scientific, technological, economic, societal and political conditions can be expected to change significantly over the time span during which a disposal programme is developed and implemented.

Another particular aspect of a disposal programme is the potentially long time span between when funding for the project is acquired and when the actual expenses arise. The most common principle is that the waste producer is responsible for all the costs of the waste management, including disposal. For nuclear power generation, this cost is generally included in the production cost and should be covered by power production revenues. Since disposal activities are likely to continue long after the electricity production of the nuclear power plant has stopped, the collection of funds needs to be undertaken in advance of plant closure. The cost estimates therefore have to take account of the disposal project long before its implementation to assess the required funding. This in turn can be complicated by the fact that the final disposal option or the waste inventory for disposal is not always known at the time of the cost estimate. Sometimes, much of the waste has not yet been generated at the time of the cost estimate; and, due to past practice, some existing waste may not have been well characterized and its properties therefore might also be uncertain.

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[1] A near surface disposal facility is located at or within a few tens of metres of the Earth's surface [4]. A geological disposal facility is located underground, usually several hundred metres or more below the surface, in a stable geological formation to provide long term isolation of radionuclides from the biosphere [4].

It is clear that sustainable disposal programmes cannot be maintained without adequate and reliable costing methods and associated funding schemes. Developing such methods and schemes is, however, not straightforward. Several reports have been published on the costing and funding of radioactive waste management in general, and of waste disposal in particular (see Refs [6–15]). Reference [7] provides general guidelines for estimating the cost of the life cycle of a disposal facility and possible funding mechanisms, and concerns the disposal of LLW and ILW.

The OECD Nuclear Energy Agency (OECD/NEA) publication on the economics of the back end of the nuclear fuel cycle is an extensive report focusing on the long term management of spent fuel and HLW [11]. Its scope is wider than waste disposal, addressing interim storage and spent fuel reprocessing. The report contains much information and data on the cost of various options for long term radioactive waste management in different countries.

The International Association for Environmentally Safe Disposal of Radioactive Materials (EDRAM) 2013 report compares cost assessment methods for geological disposal [13]. The goal was to develop a list with cost items for a geological disposal programme which could be used to compare and peer review the cost of these items and concluded that:

> "...a simplified comparison of cost assessments for geological repository projects is not possible or would produce distorted conclusions. A sound comparison implicates a 'deconstruction' of the cost estimates and a good knowledge of the related waste inventories."

1.2. OBJECTIVE

With this publication, the IAEA aims to provide Member States with guidelines on how to develop cost estimates for a disposal programme and how to establish funding schemes. The publication will help readers to gain an understanding of the approaches, difficulties and complexities in cost estimates and funding mechanisms for disposal programmes. Developing such estimates and funding schemes, however, requires expertise, and experts in this field need to perform or support these tasks.

These practical guidelines will provide Member States with an insight in how cost estimates and funding schemes for their disposal programmes can be established. One such example is the inclusion of work breakdown structure (WBS) of a generic disposal programme. As a disposal programme contains many diverse activities and can become very extensive, assessing its cost can only be done once all the activities have been identified. Therefore, a WBS of a disposal programme can be a useful tool to list the activities and items of a disposal programme and to structure them in a logical manner before the cost of the WBS items are assessed.

This publication is aimed at decision makers, project managers working within radioactive waste management organizations charged with implementing disposal programmes, and to those who need to understand the associated financial liabilities and those who are to establish schemes for the necessary funding. In addition, service organizations (research and commercial) and regulatory authorities will also find the information in this publication to be beneficial.

This publication is relevant both to implementers managing an advanced disposal programme and to those taking the first steps or in the early planning phase of such a programme. The former might take an interest in comparing their experiences and approach to the ones presented here. The latter can find specific guidelines on how to develop cost estimates and funding schemes.

1.3. SCOPE

This publication considers both near surface and geological disposal. It includes the cost of the research, design and development (RD&D) necessary to develop the programme, the actual implementation of the programme and the costs of societal participation activities. The necessary activities prior to disposal, such as radioactive waste treatment, conditioning and prior storage, are not included. It does, however, include the cost of final conditioning into a disposal container, to the extent that this is called for by the design of the disposal facility, as well as the cost of any interim or buffer storage needed to accommodate waste streams towards disposal. Guidelines on cost estimates and funding of activities prior to disposal are provided in Refs [7, 9, 12]. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.4. STRUCTURE

Section 2 presents strategies and options for waste management. Section 3 provides an introduction to cost estimates of disposal programmes. Guidelines on how to assess the overnight[2] cost of a disposal programme without including the cost impact of the risks and uncertainties of disposal programmes are given in Section 4. Sections 5 and 6 explore the WBS cost estimate and the cost impact of those risks and uncertainties, respectively. Section 7 describes the funding schemes for a disposal programme, and Section 8 summarizes the main conclusions.

For simplicity, all costs in this publication are expressed in US dollars. The conversion of other currencies to US dollars is done using purchasing power parities (PPPs). These are conversion rates that equalize the purchasing power of different countries by eliminating differences in price levels. The OECD [16] defines PPPs as the rates of currency conversion that “equalise their purchasing power by eliminating the differences in price levels between countries.”

> “...In their simplest form, PPPs are nothing more than price relatives that show the ratio of the prices in national currencies of the same good or service in different countries. ...
>
> “Exchange rates are determined by the supply and demand for different currencies. But the supply and demand for currencies are influenced by factors such as currency speculation, interest rates, government intervention and capital flows between countries rather than by the currency requirements of international trade. Moreover, many goods and services, such as buildings, all government services and most market services, are not traded internationally. For these reasons, exchange rates do not reflect the relative purchasing powers of currencies in their national markets.”

PPPs are preferred here to the more volatile currency conversion rates (see the Annex for the PPPs used in this publication).

2. WASTE MANAGEMENT POLICY, STRATEGIES AND OPTIONS

Developing a disposal programme is preferably preceded by, and embedded in, a national waste management policy and strategy framework. The policy defines the goals and principles of waste management, and the strategy describes the approach for implementing it. A well defined policy and associated strategies can promote consistency between the actions and plans of all parties or sectors involved in waste management. More comprehensive and specific guidance on developing a waste management policy and strategy is given in Ref. [3]. A concise summary of key issues relating to the development of a sound radioactive waste and spent fuel management system is given in Ref. [17].

Developing a relevant waste strategy requires knowledge of the available technical options for waste management. Waste management activities include waste collection, characterization and segregation, treatment, conditioning, storage and disposal. Not all options may be needed for different waste types (see Section 2.3 for the range of options).

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[2] The overnight cost is the cost as if the programme were implemented overnight. In Canada and the United States of America, this is usually referred to as the constant dollar cost. The constant dollar cost gives a conversion of costs that are spread out over different years in dollar cost for a given base year. This removes the effects of cost escalation.

2.1. POLICY

It is implied in the Joint Convention [2] that States should have policies relating to the management of their radioactive waste. Reference [3] states:

> "A policy for spent fuel and radioactive waste management should include a set of goals or requirements to ensure the safe and efficient management of spent fuel and radioactive waste in the country."

Furthermore according to Ref. [3], a national policy "must represent the views of all of the organizations concerned in the management of spent fuel and radioactive waste" and it "should reflect national priorities, circumstances, structures, and human and financial resources", as well as the "type and the characteristics of the radioactive waste, and the geographical distribution of the radioactive waste and of the population". Reference [3] states:

> "In order to formulate a meaningful policy, it is necessary to have sufficient information on the national situation, for example, on the existing national legal framework, institutional structures, relevant international obligations, other relevant national policies and strategies, indicative waste and spent fuel inventories, the availability of resources, the situation in other countries and the preferences of the major interested parties."

Examples of other national policies with a potential impact on the waste management policy are those dealing with other hazardous materials, nuclear electricity production and spent fuel reprocessing.

IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [1], can assist policy makers. The principles specific to radioactive waste management are described in Ref. [3]. They provide a commonly understood basis for guiding all activities relating to the safe management of radioactive waste. The policy will [3]:

(a) Provide a basis for a legal and regulatory framework for waste management;
(b) Define roles and allocate responsibilities concerning the waste management;
(c) Provide a basis for developing a safe and sustainable waste management programme;
(d) Provide for the adequate allocation of financial and human resources over time;
(e) Enhance public confidence in waste management.

The policy will subsequently be translated into a waste management strategy (see Section 2.2).

2.1.1. Basis for legal and regulatory framework

The policy needs to be consistent with existing legislation and other national policies. In turn, the policy will serve as a basis for further developing the legal framework for waste management and specifying the regulatory framework for its implementation.

2.1.2. Definition and allocation of roles

Reference [3] states:

> "It is important for there to be clarity concerning national responsibilities for managing spent fuel and radioactive waste. Thus, the national policy should identify:
>
> — The government organization(s) responsible for establishing the legislative and regulatory framework;
> — The relevant regulatory body;
> — The organization(s) responsible for ensuring that radioactive waste is safely managed (normally the licencee);
> — The organization(s) responsible for the long term management of spent fuel and radioactive waste, and for radioactive waste for which no other organization has responsibility.

....

"Other governmental bodies may have roles in the process, for example, government organizations concerned with environmental protection and the transport of radioactive material as well as local governmental organizations."

2.1.3. Basis for waste management programme development

The policy can set out the direction for developing the waste management programme and provide a direction or target goals for all sectors involved [3]:

"A well defined policy and associated strategies are useful in promoting consistency of emphasis and direction within all of the sectors involved in spent fuel and radioactive waste management. The absence of policy and strategy can lead to confusion or lack of coordination and direction.

"A policy and/or strategy may sometimes be needed to prevent inaction on a particular waste management issue or to resolve an impasse."

2.1.4. Adequate allocation of financial and human resources

Article 22 of the Joint Convention [2] requires that:

"Each Contracting Party shall take the appropriate steps to ensure that:

(i) qualified staff are available as needed for safety related activities during the operating lifetime of a spent fuel and a radioactive waste management facility;
(ii) adequate financial resources are available to support the safety of facilities for spent fuel and radioactive waste management during their operating lifetime and for decommissioning;
(iii) financial provision is made which will enable the appropriate institutional controls and monitoring arrangements to be continued for the period deemed necessary following the closure of a disposal facility."

Reference [3] states:

"Thus, the national policy should set out the arrangements for:

— Establishing the mechanisms for providing the resources or funds for the safe, long term management of spent fuel and radioactive waste;
— Ensuring that there are adequate human resources available to provide for the safe management of spent fuel and radioactive waste, including, as necessary, resources for training and R&D;
— Providing institutional controls and monitoring arrangements to ensure the safety of spent fuel and radioactive waste storage facilities and waste repositories during operation and after closure.

"This is discussed in detail in Ref. [7]."

2.1.5. Public confidence enhancement

Reference [3] states:

"The national policy may indicate the State's intention to inform the public about proposed plans for radioactive waste management, and to consult concerned parties and members of the public to aid in making related decisions (Paragraph (iv) of the Preamble of the Joint Convention [2] and Ref. [18]). Nowadays, governments tend to emphasize their commitment to policies of openness and transparency in relation to their intentions and plans on radioactive waste management.”

2.2. STRATEGIES

Once a policy has been established, the approach to implement it is described in the waste management strategy. Several individual strategies might be developed, addressing, for example, different waste types or waste from different owners. Developing the strategy requires more detailed information on the organizational, technical and legislative situation in the country and on future needs and waste generation. An understanding of the following topics is necessary:

(a) The radioactive waste that needs to be managed;
(b) The legal and regulatory framework for waste management;
(c) The existing institutional framework for waste management;
(d) The expectations of stakeholders;
(e) The available waste management options.

The waste management options concern the technical options to collect, characterize and segregate the waste, treat and condition it, and then store it. Waste storage can only be a final solution for very short lived waste (VSLW). For other waste types, storage is an interim solution pending disposal. The waste disposal options are discussed separately in Section 2.3.

Knowledge of waste management strategies in other countries can be useful, as these can give guidance and serve as an example. It is, however, important to keep in mind that each country has its own specific situation [3]:

> “There is great diversity in the types and amounts of radioactive waste in different countries and, as a result, the strategies for implementing the policies are sometimes different.
>
> ....
>
> “The strategies adopted may also depend on the national availability of waste management competence, facilities and technology.”

2.2.1. Radioactive waste inventory

When developing a strategy for waste management, it will be necessary to obtain a sufficiently accurate idea of the waste to be managed. The type and quantity of waste will determine the disposal options that can be considered and the size of the disposal facility required. It is therefore necessary to determine and, in the case of future waste, to predict the volume, production rate, schedule and characteristics of the waste inventory.

At the early stage of establishing a waste management strategy, it might be difficult to acquire a complete view of the waste inventory, so a prediction is needed of how much waste will be generated and what its characteristics will be. Historic wastes might not have been well characterized, and there may be uncertainties about their properties. It is therefore likely that there are unknowns about the waste inventory and so certain assumptions will need to be made.

A scheme for classifying the radioactive waste will also need to have been established. IAEA Safety Standards Series No. GSG-1, Classification of Radioactive Waste [19], sets out a general scheme for classifying radioactive waste that is based primarily on considerations of long term safety, and thus by implication, disposal of the waste.

2.2.2. Legal and regulatory framework

Prior to developing a waste management strategy, the legal framework under which the waste management will operate needs to be established, together with the regulatory framework defining how the waste management activities are to be regulated. The government is responsible for establishing this framework and needs to designate an independent regulatory body to enforce the waste management regulations (arts 19 and 20 of the Joint Convention [2]). IAEA Safety Standards Series No. GSR Part 1 (Rev. 1), Governmental, Legal and Regulatory Framework for Safety [20]:

> "covers the essential aspects of the governmental and legal framework for establishing a regulatory body and for taking other actions necessary to ensure the effective regulatory control of facilities and activities — existing and new — utilized for peaceful purposes".

2.2.3. Institutional framework

Reference [3] states:

> "Implementation of the policy requires that there is an adequate and appropriate waste management institutional framework in the country. ...This framework should include two basic bodies: an organization, or organizations, devoted to coordinating or overseeing radioactive waste management, and an independent regulatory body established to enforce the implementation of the regulations on spent fuel and radioactive waste management."

Both organizations need to have the financial, human and technical resources to establish and implement the radioactive waste management programme. The financial resources will originate either directly or indirectly from the funding mechanisms established for the management of the waste. The costs associated with the waste management activities of these organizations should be included in the overall waste management cost assessment. In turn, the funding mechanisms have to ensure that the implementing and regulating organizations have the human resources to do their work. This is addressed in Section 5, on cost assessment, and Section 7, on funding mechanisms.

2.2.4. Stakeholder expectations

It is important to develop the waste management policy and strategy in consultation with all stakeholders in waste management, which comprise governmental bodies and regulators, the waste producers and organizations responsible for managing the waste (e.g. technical support organizations), local communities or the general public, non-governmental organizations, research institutions and advisory and consultative bodies. The types of stakeholder depend on the particulars of the State's relevant legislation and the appropriate strategy on stakeholder communication and involvement.

The attitudes and expectations of different stakeholders may result in formulating specific requirements or boundary conditions on the waste management strategy itself, and need to be understood. Experience in many countries has shown that transparency and openness on waste management plans that may affect local communities offer the best chance of success [3]. Local communities should therefore be involved from the very beginning in the waste management plans and their expectations should be understood and taken into account. Guidelines and examples of approaches in communication and stakeholder involvement associated with radioactive waste disposal are given in Ref. [21].

2.3. WASTE DISPOSAL OPTIONS

Apart from VSLW, for which decay storage can be the final step in waste management, radioactive waste will ultimately need to be disposed of. Waste disposal means that the waste will be emplaced into a facility or a location with no intention of retrieval [4]. The disposal facility is located and designed to isolate the waste from any surface based disturbances and to ensure that the host geological formation and the disposal system's engineered barriers provide for safe containment. Although disposal implies that waste retrieval is not intended, it does not mean that it is not possible [22]. In some programmes, retrievability is a regulatory requirement for a certain period of time.

Wastes with varying amounts of long lived radionuclides require longer periods of containment and isolation and thus different disposal solutions. The IAEA waste classification scheme provides a direct link between the waste class and the suitable disposal options [19]. This section presents an overview of disposal facilities that are now in use or are planned.

The strategy can call for immediate waste disposal. In practice, however, the disposal is often deferred because:

(a) Facilities for predisposal or disposal are unavailable.
(b) Accumulating waste can lead to a more effective and economic waste processing.
(c) A final decision on the ultimate disposal solution is pending.
(d) The thermal output of HLW packages needs to decrease prior to their disposal.

States may also consider sharing dedicated waste management facilities with other States (see Ref. [23]). Pursuit of a multinational approach, however, needs to include a commitment to a national solution. This is called a dual track approach where the multinational disposal solution is considered in parallel to a national one.

2.3.1. Trenches

Trenches are facilities similar to conventional landfills for industrial and domestic waste. They are a cost effective option for large volumes of VLLW, and may include large items of decommissioning waste [24].

In arid regions with low rainfall and deep groundwater, such as Vaalputs in South Africa (see Fig. 1), LLW is disposed of in trenches with limited or no isolation layers. Sometimes polyethylene, clay or geotextile barriers are used to avoid or limit groundwater infiltration. The potential risk of inadvertent intrusion can be limited by engineered barriers and by a sufficiently long period of institutional control.

2.3.2. Engineered structures

Engineered structures are facilities built on or just below the ground surface. They mainly differ from trenches because the engineered barrier system is a more elaborate system comprising a more robust set of multiple layers. The design takes account of the type of waste and required durability and offers a disposal option for LLW.

As for all disposal concepts, the long term safety is provided by a combination of natural and engineered barriers. The design of the engineered barrier system depends on the site conditions and, in particular, on the local geology and hydrogeology, and has to limit or delay radionuclide migration from the facility.

Typically, such facilities consist of an array of concrete vaults in which the waste packages are emplaced. The facility is capped by an impermeable, multilayer cover and voids in the vaults are backfilled after waste emplacement. Drainage systems can be installed to help limit water ingress and vault inspection can be facilitated via inspection galleries around or below the facility. An example of such a facility is the planned surface disposal facility for LLW in Belgium (see Fig. 2).

Engineered structures for waste disposal are generally located above the groundwater level, although their construction in the saturated zone is possible provided that they are adequately designed for such an environment.

FIG. 1. Vaalputs disposal facility for LLW, South Africa (courtesy of South African Nuclear Energy Corporation).

FIG. 2. Artist's impressions of the planned surface disposal facility for LLW in Belgium. Note: Concrete waste packages are to be placed in concrete vaults with a temporary cover during the operational phase (top); after waste emplacement the vaults will be backfilled and the temporary cover replaced by a permanent multilayer one (bottom) (courtesy of ONDRAF/NIRAS).

2.3.3. Disposal facilities at intermediate depth

Underground caverns at depths in the order of tens of metres to a few hundred metres can be used as disposal facilities for LLW and ILW. Their detailed design depends on the waste type and geological environment. After waste emplacement operations are completed, the facility will be backfilled and sealed.

The natural barrier is expected to contribute more to long term safety in a cavern facility than in trenches and engineered structures. The geological formation surrounding and protecting the facility will contribute to retarding and delaying radionuclide releases to the biosphere. The greater depth of these facilities also makes them more secure against human or animal intrusion. A more extensive engineered barrier system might be needed, however, to limit water movement, especially if the facility is below the groundwater table.

Constructing and operating underground facilities requires the use of adequate mining engineering techniques, controlling and monitoring rock or soil deformations and continuously ventilating the facility. Mining regulations probably apply and fire risk management can be more complicated than for surface disposal facilities. Figure 3 shows the layout of such a cavern type facility, located 80 m below sea level in the Republic of Korea. It is a silo with a diameter of 24 m and is one of six identical silos making up a repository for LLW and ILW.

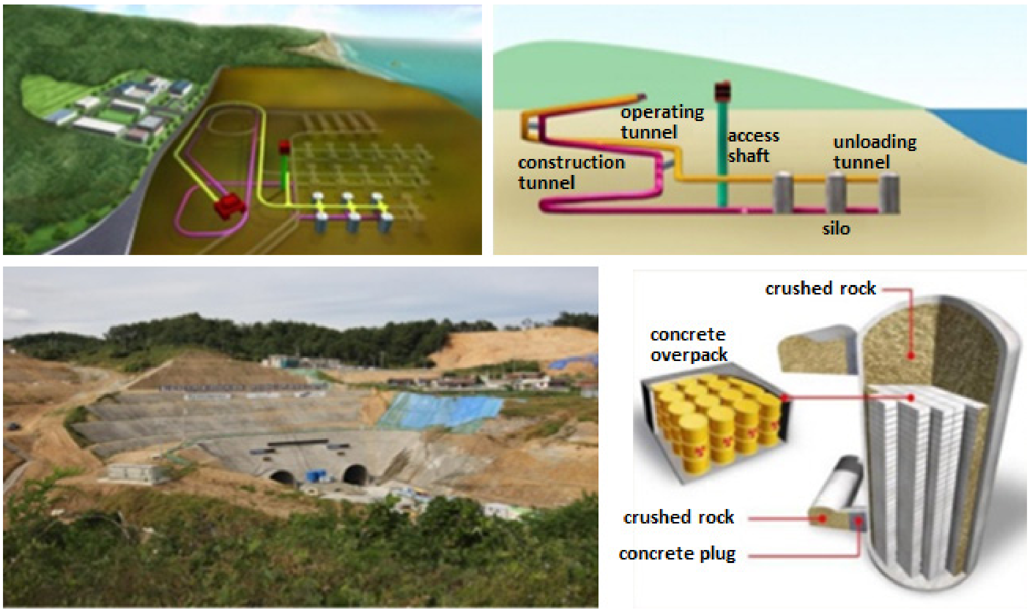

FIG. 3. Silo for the disposal of LLW and ILW in the Republic of Korea (courtesy of Korea Radioactive Waste Agency).

2.3.4. Geological disposal facility

HLWs need to be isolated from the biosphere for tens to hundreds of thousands of years. The relevant timescale and specific need for containment and isolation depend on the specific waste properties and have to be demonstrated for as long as the waste presents a potential hazard. It is not possible to ensure this level of isolation in facilities at the surface or at depths in the order of tens of metres to a few hundred metres. These types of waste require disposal at a depth of several hundred metres in a stable geological environment that can provide isolation and containment for the needed timescale. This disposal option is referred to as geological disposal.

The natural and engineered barriers need to isolate the waste and retard, delay and attenuate the migration of radionuclides so that radionuclide releases into the biosphere do not pose a hazard to people and the environment. This places high requirements on the geological environment in which a geological disposal facility is located. It needs to be a geologically stable environment with low seismic activity or active faults, where water movement is slow and in which the groundwater chemistry is favourable for ensuring adequate safety performance of the disposal system.

Designs for geological disposal repositories have been developed for a range of geological environments such as salt, crystalline rock and clay formations. The Waste Isolation Pilot Plant (WIPP) facility is a geological disposal facility in the United States of America at a depth of around 650 m in an embedded salt formation where transuranic waste (waste contaminated by elements heavier than uranium) arising from defence related operations has been disposed of since 1999 (see Fig. 4) [25].

2.3.5. Borehole disposal facility

Borehole disposal entails the emplacement of waste canisters in one or more boreholes. Possible borehole depths range from a few tens of metres up to several hundred metres. The diameter may vary from a few tens of centimetres up to a few metres. After lowering a waste package down the borehole, the borehole may be filled with a buffer material to fill the annular space around the waste packages and, usually, to ensure that the waste packages are not stacked directly on top of one another.

Borehole disposal can offer an economically interesting option for small waste inventories as their construction and operation costs are generally lower than those of surface facilities or geological repositories. The disposal of disused sealed radioactive sources, for example, can be done more cost effectively in boreholes tens of metres deep (generally not more than 150 m) [26].

Figure 5 shows a concept for the borehole disposal of disused sealed radioactive sources. This concept has been extensively studied and some Member States are currently progressing towards implementing this concept.

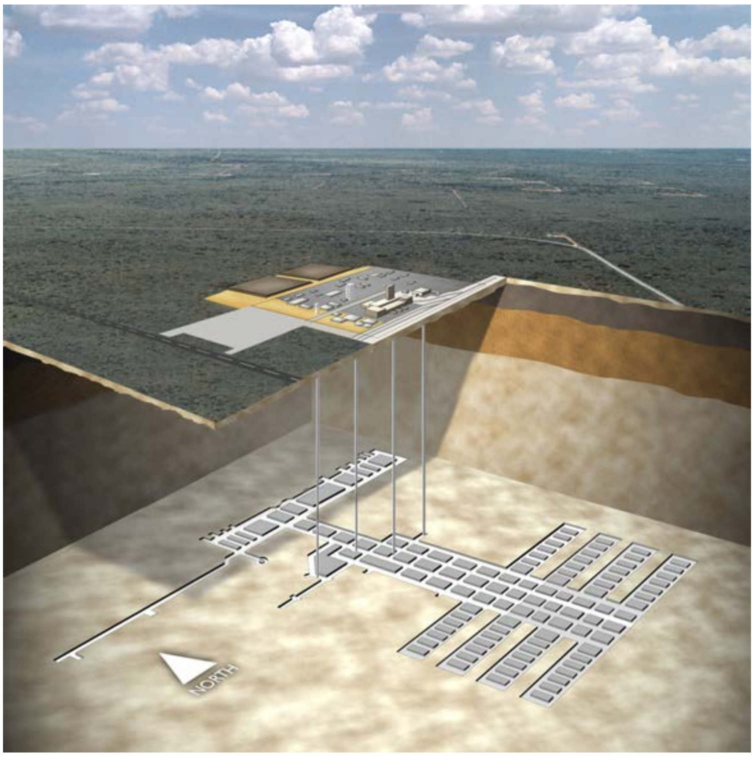

FIG. 4. WIPP facility at a depth of ca. 650 m in a salt formation in New Mexico, USA (courtesy of USDOE).

One of its specificities is the comparatively small borehole diameter, consistent with conventional water borehole drilling equipment. Depending on the site's specific properties, the disposal zone would typically be in a geological formation at intermediate depth. The overall project costs, from initial studies over licensing to implementation, would be several million US dollars.

Disposal at depths of several kilometres has also been considered [27, 28]. The safety strategy of such very deep disposal consists of isolating the waste in an environment where the groundwater is unlikely to interact with the biosphere. The stagnant groundwater conditions at great depths result from the density stratification that is caused by the increasing salinity of the groundwater with depth.

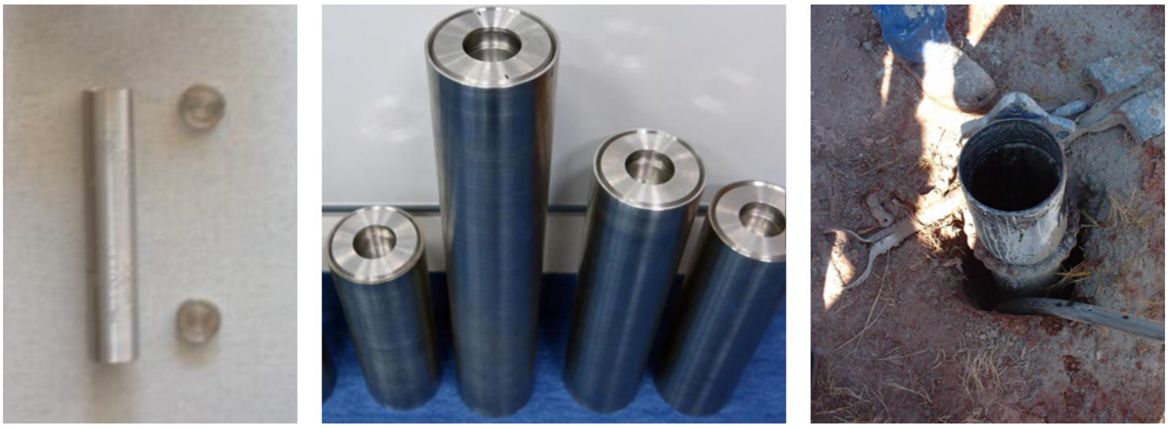

FIG. 5. Borehole disposal of disused sealed radioactive sources. Note: (from left to right) The sources are placed in capsules which in turn are conditioned in waste packages before they are disposed of in a borehole.

3. COST ESTIMATE METHOD

Key to developing a cost estimate for a disposal programme is an adequate understanding of the programme and the purpose of the estimate. These should be clearly documented in a baseline document, which describes the disposal programme and the elements to be included in or excluded from the estimate. The document will also contain a lifetime plan of the disposal programme. Such a plan sets out the major deliverables and activities of the programme and the schedule for delivering them.

The baseline document serves as the basis for the cost estimate. It provides traceability and aids in justifying the assumptions and principles that underlie the estimate, and it will be a crucial document when updating or reviewing the estimate.

The baseline document also describes the purpose of the estimate. Estimates can be made for different reasons and the purpose determines the method used. When an estimate is used to support a relative comparison of different radioactive waste disposal options, which are only conceptual at this stage and not detailed, then it might not be useful, or even possible, to develop the estimate in great detail. In such a case, an analogous approach to costing might be enough, or rather it may be the only method that can be used, as the data for a more detailed breakdown might not be available. However, when the disposal project is coming close to being implemented, a more detailed cost estimate will be necessary for budget planning. This requires a detailed WBS, and the methodology to develop this should be commensurate with the purpose of the estimate.

The level of detail of the baseline document will clearly depend on the development stage of the disposal programme and on the amount of time and resources available for this task. Programmes in an early phase may still be immature and their baseline description will be imprecise or incomplete. It is nevertheless important to try to develop a baseline description that covers all aspects of the disposal programme and that is as complete as possible. This will require that various assumptions are made about the unknowns within the programme, including the justification for the assumptions. Possibly, alternative programmes and alternative scenarios can be described in separate baseline documents.

When the programme evolves or changes, the baseline will be updated or adapted. The cost estimate will also be periodically updated, based on the latest version of the baseline description. This ensures that the state of the disposal programme for which the cost is estimated is clearly documented and that the underlying assumptions are identified. In addition, it provides traceability of changes to the disposal programme and the related cost estimate.

Once the programme and the assumptions are documented in the baseline description, its cost can be estimated. A number of reports have been published giving guidance on developing cost estimates of large projects.

(a) The United States Department of Energy (USDOE) compiled a cost estimating guide in 2007 [29], the aim of which is to improve the quality of cost estimates by providing uniform and consistent cost estimating methods and terminology.
(b) In the United Kingdom, HM Treasury publishes the Green Book [30], which provides procedures for assessing and evaluating the economic, financial, social and environmental impacts of those proposals for government projects, policies and programmes. There is a wide range of supplementary Green Book guidance on particular issues and on applying the procedures in different contexts.
(c) The AACE International publication on total cost management presents “a systematic approach to managing cost throughout the life cycle of any enterprise, program, facility, project, product or service” [31].
(d) The National Aeronautics and Space Administration (NASA) publishes a guide for cost estimating at NASA [32]: “The intended audience covers the non-estimating professional and the new cost estimator, as well as experienced analysts.”
(e) The United States Government Accountability Office (USGAO) published an extensive guide in 2020 on estimating and assessing the cost of capital programmes [33], the purpose of which is “to establish a consistent methodology based on best practices that can be used across the federal government for developing, managing, and evaluating program cost estimates”.

In Ref. [33], three commonly used methods for estimating costs are described: analogy, engineering buildup and parametric. Which method is used depends on the maturity of the programme, the availability of comparable programmes and cost information on those programmes, and the time and expertise available to perform cost estimates.

The analogy approach uses the costs of similar programmes and adjusts for differences. The adjustments can entail updating old cost estimates or adjusting for differences in quantities, size or complexity. The analogy method is usually used at an early stage of the programme when the programme is not sufficiently well defined to be able to make an accurate cost estimate, but its content is sufficiently clear to be able to make the necessary adjustments.

The engineering buildup method, also called the bottom-up method, first breaks the programme down into more specific components which are laid out as a WBS. Subsequently, the costs of the WBS components are estimated. Their summation results in an overall cost estimate of the complete programme.

The parametric method develops a statistical relationship between the programme and its cost based on historical data. Developing such a statistical relationship requires that enough historical data exist and can be accessed. This method is therefore mainly applicable to projects for which a large set of cost data are available for the various parameters. This is not the case for some parts of the waste disposal programme. Disposal programmes that have been implemented or completed are rather scarce and in addition, there is a large variability in the programmes and their costs.

The analogy method can be applied by using the cost of more advanced programmes. Several publications analyse the cost of different disposal programmes and evaluate the potential for comparing their costs (see Refs [11, 13, 34]). They all conclude that there is a high variability in disposal programme costs and that it is very difficult to compare them. The high cost variability results from the significant differences between the programmes of the various countries, having different waste inventories, geological environments, policies and legislation, societal contexts and economies.

The analogy method can be useful for programmes that are at a very early stage. At such an early stage, it might not be possible to define the disposal programme sufficiently accurately to apply the engineering buildup method in a meaningful way. The analogy method can then be used to obtain a rough idea or an order of magnitude of the estimate. It will, however, be important that the programme is well understood. For example, it will be important to know whether the cost figure is an overnight or constant dollar cost or whether it is a discounted cost (see Section 7), if any contingencies are built in (see Section 6) and what the reference year is, among other things. Furthermore, using the cost of another country's disposal programme might require a currency conversion. This can be based on foreign exchange rates, but it is probably more useful to use PPPs.

When the programme evolves and becomes more clearly specified, the relevance of analogues decreases and more accurate cost estimates are necessary. This can be achieved by the engineered buildup method which consists of developing a WBS of the disposal programme and then estimating the costs of the WBS items. As the programme evolves, the WBS will become more specific and detailed, and the cost estimate will become more accurate.

The analogy method can still be of use for estimating the cost of certain WBS items. Examples from the nuclear industry can give an indication of the cost of constructing and operating nuclear facilities. The mining industry can give similar information on underground waste repositories. The analogues used should, however, become more specific as the programme and cost estimate evolve. For example, it might be useful to use the cost of site characterization from another programme if it is not yet clear which activities are necessary for the site characterization in the own disposal programme. Once it becomes clear which site characterization activities are to be performed, a cost estimate needs to be done for these specific activities. Guidelines on developing a WBS and assessing the cost of the WBS items are given in Sections 4 and 5.

The engineering buildup method will result in a single value for the programme's cost, a so-called point estimate. This outcome is however uncertain as it relies on a defined design and scenario containing assumptions or predictions. The uncertainties on the cost estimate will decrease as the programme becomes more specific and mature. In addition, risks are always present that the design and scenario will be overturned. Such risks have in the past often materialized in waste disposal programmes that generally expand over decades and operate under conditions (e.g. political, societal, economic, scientific) that can change over such long time periods.

It is therefore best practice to have a range of cost values around the point estimate reflecting the degree of uncertainty and the level of confidence in achieving the point estimate cost. The cost uncertainty and range of values are larger for programmes in an early phase containing many unknowns. As the programme evolves, the number and degree of the unknowns decrease and the range of values becomes narrower. Past experience suggests that the point estimate increases as the programme becomes more specific. This increase can be caused by cost elements that were overlooked at the very early stage and became apparent when the programme became more specific. Section 6 explains how uncertainties and risks can be taken into account in disposal programme cost estimates.

When the cost of the WBS components is assessed, this concerns their cost as of today. The summation of these costs will therefore result in the overnight cost of the disposal programme, which is the cost of the programme were it to be implemented overnight. The implementation of the programme will, however, take many years or even decades. Therefore, when determining the provisions that are needed today to finance the programme, economic changes, such as inflation, need to be taken into account.

It is therefore necessary to draw up the disposal programme's planning so as to indicate when the costs for the WBS components will occur. In other words, the overnight costs are distributed over the lifetime plan of the disposal programme.

To determine the provisions that are needed today to finance this disposal programme, these costs have to be discounted to today using an appropriate discount rate. Future economic changes need to be assumed or predicted, which adds another uncertainty on the provisions that need to be acquired for funding the programme. The discounting of the overnight costs is further explained in Section 7, where the funding schemes for the disposal programme are discussed. As explained in Section 7, the planning or schedule of the programme can have a large impact on the discounted cost. It is therefore important that sufficient attention is given to drawing up a planning that is as accurate and underbuilt as possible and describe the planning in the baseline document. In conclusion, the approach to estimating a disposal programme's cost consists of the following steps:

(1) A baseline document defines the disposal programme, explains the purpose of the cost estimate and identifies the assumptions about the unknowns in the programme;
(2) A WBS of the programme is made, dividing it into more specific components;
(3) The overnight cost of these components is estimated;
(4) The cost impact of uncertainties and risks related to the disposal programme is assessed and taken into account;
(5) The overnight cost is converted into a discounted cost, which will be used to determine the provision needed to finance the disposal programme.

Sections 4–7 reflect this logic and explore steps (2)–(5). It is important to note as well that it will be vital to regularly update the cost estimate. This has to ensure that the estimate remains in line with the disposal programme and that possible fund contributions based on the estimate are sufficiently up to date. In several countries, the frequency at which cost updates need to be made is regulated. For example, the Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering AB, SKB) needs to submit a cost estimate to its regulator every three years [35]; and in Switzerland, cost estimate updates are conducted every five years, at reactor shutdown or whenever unexpected circumstances with a significant cost impact occur [36].

4. WORK BREAKDOWN STRUCTURE OF THE DISPOSAL PROGRAMME

A disposal programme contains a broad range of activities. To obtain a sufficiently accurate and meaningful cost estimate, it is necessary to first divide the programme into a series of smaller and more specific components by establishing a WBS. The WBS can also serve as a valuable communication tool, as it draws a clear picture of the work the programme entails and provides a framework for planning and allocating responsibilities for the work.

In this section, the breakdown of a generic disposal programme is presented. It presents the disposal programme from the perspective of the waste management organization (WMO), since it will be responsible for implementing the programme. In most cases, it will also be the WMO which estimates the disposal programme cost. The WBS is applicable to the geological and near surface disposal of all waste categories, including spent fuel declared as waste.

Rather than developing a more detailed WBS, the breakdown structure presented here is not as detailed as the International Structure for Decommissioning Costing developed for decommissioning projects [10]. The more detailed description of the high level components further in this section should also not be seen as an exhaustive list of items that should be included. They are only examples of items that may be included in the given WBS component.

The WBS concerns only the disposal of the radioactive waste and not the overall waste management. The latter has a wider scope, encompassing activities such as waste characterization, treatment, transport and storage. It may be that predisposal activities, such as waste storage can be part of the disposal programme, and waste transport from interim storage to disposal might, for example, be considered as a part of the disposal programme.

It is up to each State to decide which waste management activities are to be included in the cost estimation. This can differ from country to country. What needs to be understood, however, is that the entire back end management responsibilities needs be provided — and paid — for. This means that any activity not included in the disposal programme has to be included elsewhere and possibly paid for from a separate source.

A disposal programme can be broken down in different ways and the WBS presented here reflects just one possible way of doing it. Figure 6 shows how the WBS can be structured according to the following four components of a disposal programme:

(a) Disposal programme management: The activities relating to running the organization responsible for developing and implementing the disposal system.
(b) Stakeholder involvement: Involving stakeholders in the disposal programme.
(c) Disposal system development: The RD&D providing and demonstrating the scientific and technical basis, and developing and maintaining the safety case for the disposal facility.
(d) Disposal implementation: The construction, operation and closure of the disposal facility.

These components are relevant to both near surface and geological disposal programmes, as the types of activity needed to be carried out are similar. Both types of programme require, for example, site selection, characterization, development of a scientific and technical basis, and development of a safety case and safety assessment. The extent and complexity of these activities can, however, be very different for near surface and geological disposal, leading to significant differences in costs.

Development of a WBS implies that a decision has been taken to set up a disposal programme. This decision serves as a sort of starting point. It is also assumed that the legal and regulatory framework has already been developed. It furthermore tries to be as complete as possible, providing an envelope of activities which should be included in such a disposal programme. This does not mean that all activities will need to be included. Certain WBS items will not be relevant for some disposal programmes. This may be either because (i) some specific items are not needed in every programme or (ii) some specific items may be considered out of the scope of the national disposal programme, as they are included under another element in the national waste management activities.

Finally, the end point of the disposal programme needs to be defined. Some programmes may consider that the end point is reached at the physical closure, decommissioning and delicensing of the surface facilities, after which any long term post-closure responsibilities fall to the national budget. Other programmes might include a surveillance or monitoring period after closure or decommissioning of the site.

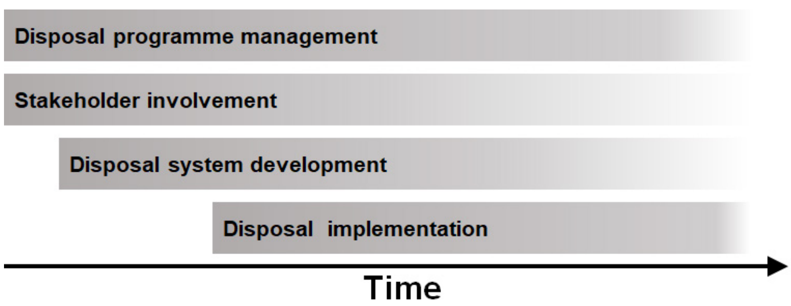

FIG. 6. Thematic breakdown in distinct types of activity (which can overlap in time).

4.1. DISPOSAL PROGRAMME MANAGEMENT

Many Member States have founded a WMO or entrusted this function to an existing institution which is then responsible for developing and implementing a waste disposal programme. The range of tasks undertaken by this organization can vary. It can consist of developing disposal facilities, but it may have predisposal management responsibilities as well. These may include providing facilities for treatment, conditioning, storage and transport. As mentioned before, each Member State or each WMO has to decide for itself where the boundary lies between waste disposal and predisposal waste management. This component contains all activities carried out by the WMO and may include:

(a) Those activities necessary to run the WMO, such as human resource management, financial and commercial management, quality management and IT. General functions typically found in almost all medium sized to large organizations include directors, administrative assistants, quality managers, IT technicians, legal advisers and accountants.
(b) WMO staff occupied with establishing stakeholder involvement, such as communication staff.
(c) WMO staff working on disposal system development, mainly as engineers and scientists.
(d) External consultants.

Offices, utilities and equipment needed for running the organization are also included in disposal programme management. Another way of breaking down the disposal programme is to include those WMO activities specific to stakeholder involvement, disposal system development or project implementation in those breakdown components (see Sections 4.2–4.4). Again, there is no correct or incorrect way of doing it. The main point is not to forget or overlook certain activities or cost items.

4.2. STAKEHOLDER INVOLVEMENT

Stakeholder involvement concerns the activities undertaken to create a dialogue with the broad range of stakeholders and include them in the development and implementation of the disposal programme. Stakeholders can differ from one Member State to another, depending on the particulars of the relevant legislation and national context. Possible stakeholders include:

(a) Regulatory authorities (local, regional and national authorities, environmental authorities), including the regulatory body;
(b) Local communities involved in the site selection process or hosting the disposal facility;
(c) Waste producers;
(d) Other stakeholders such as the public at large, the media, environmental organizations, non-governmental organizations, neighbouring countries and cities.

Organizing stakeholder involvement requires establishing a communications strategy and a plan for implementing this strategy. Reference [37] sets out the important steps to be included in such a plan, such as identifying and prioritizing the stakeholder groups and identifying the tools and approaches that will be used. Specific guidelines on involving stakeholders in the development and implementation of a disposal programme can be found in Ref. [21], which also describes the range of activities that can be undertaken to involve stakeholders.

As explained in Section 4.1, the WMO staff occupied with establishing stakeholder involvement is already included under disposal programme management. It should also be noted that the stakeholder involvement considered here only concerns the efforts undertaken and driven by the WMO to involve stakeholders. Regulators and others can also seek stakeholder involvement. This is, however, outside the scope of this WBS and of the report in general. Incorporating any specific stakeholder requirements in, for example, the disposal design is part of the disposal system development (see Section 4.3).

4.2.1. Regulatory authorities

The main authority is the regulatory body or bodies overseeing the disposal programme. They will assess and follow up the different disposal programme licences and authorizations (site investigation, repository construction, operation, closure, post-closure), depending on the national licensing approach. A wide variety of other authorities can play a role in the disposal programme. These can include environmental, nuclear, mining, transport or cultural authorities.

4.2.2. Local communities

Involvement of local communities can be achieved by a wide variety of activities, such as:

(a) Including public hearings as part of the permit and/or licensing process;
(b) Holding workshops, communication campaigns, information and consultation events or public debates;
(c) Establishing working groups or consultation committees;
(d) Encouraging the WMO to participate in social events;
(e) Performing sociopolitical research or cultural heritage assessment;
(f) Constructing and operating a communications centre or setting up an exhibition on waste management and disposal.

A common mechanism for public participation in the decision making process is through preparing an environmental impact assessment, which is usually made available for public commentary and can be accompanied by public hearings.

Financial incentives or potential benefits can be used for local communities to become involved in the site selection process or if a facility is developed. These are not to be seen as a compensation for real or perceived risks or impacts.

4.2.3. Waste producers

The development of the disposal programme needs to be conducted in concert with the waste producers, as their policies and plans will affect the disposal programme and, more generally, the waste management strategy. This requires that a dialogue with the waste producers is maintained on their plans (e.g. spent fuel strategy, decommissioning timeline and strategy, other nuclear plans like reprocessing, partitioning and transmutation), the waste inventory and the timing of the waste streams to be disposed of, waste acceptance criteria, and disposal programme cost optimization.

4.2.4. Other stakeholders

Other stakeholders can include the public at large, the media, non-governmental organizations, environmental organizations, trades unions, politicians, and neighbouring countries and cities. Public information can be disseminated by conducting information and consultation events, engaging national and local media, publishing newsletters, organizing site visits and operating an information centre. It will be important to establish a communication strategy to inform all parties about the disposal programme and address their views.

4.3. DISPOSAL SYSTEM DEVELOPMENT

All activities relating to developing and maintaining a safe disposal solution are grouped under the heading of disposal system development. These activities comprise, among others, initial generic considerations, site investigations and characterization, disposal facility design work, safety assessments, compiling a safety case and licence applications for construction, operation and closure. They also include the ongoing science and engineering undertaken during project implementation to maintain, update and confirm the safety case and facility design.

Disposal system development requires a solid and robust technical and scientific basis. This basis is built upon RD&D providing the data and information for the different elements that are a part of the disposal system development, such as site characterization, engineering and safety assessment. An underground research laboratory (URL), if present, is included in the RD&D if not considered as a pilot or confirmation facility. Otherwise the construction costs would be part of disposal implementation (see Section 4.4).

As explained in Section 4.1, all WMO staff working on disposal system development, mainly as engineers and scientists, should be included in the disposal programme management. Disposal system development is an iterative process that is further broken down into three consecutive phases:

(1) Process initiation;
(2) Siting and authorization for construction;
(3) Ongoing science and engineering during project implementation.

These are not necessarily discrete phases, with the next phase only commencing once the previous one has been completed. In reality, the phases will tend to merge, with some overlap of activities.

The URF Network[3] provides Member States a generic programme on the development and implementation of disposal solutions. The key phases and activities contributing to the development of a geological disposal facility are identified from an early R&D phase to later phases such as construction, operation and closure.

4.3.1. Process initiation

Before the actual development of a disposal system can start, process initiation is needed to obtain a clear — albeit initial — understanding of the following:

(a) The waste inventory and streams (including an assessment of the future inventory) that need to be disposed of;
(b) The legal framework, regulations and requirements that apply to the disposal system;
(c) The national geology and the possible geological environments in which disposal can be envisaged;
(d) The disposal options that are being developed internationally.

This is needed to understand the scope of the disposal programme (i.e. the inventory to be disposed of) as well as the legal, regulatory and environmental conditions of the national disposal programme, and the international standards, experiences and best practices available to guide development of a safe national disposal solution. Updating and maintaining this understanding is necessary throughout the entire disposal system development phase.

Understanding the regulatory and legal framework and identifying the regulatory and legal requirements for disposal are part of the process initiation of the disposal system development. If gaps in the legal and regulatory framework are identified, such gaps will need to be addressed and further regulatory development will be needed.

Stakeholder involvement is considered as a separate WBS item. Disposal system development and stakeholder involvement, however, go hand in hand. Input from stakeholders will influence the context and contours in which the disposal system needs to be developed. Stakeholders may require, for example, that the waste can be retrieved from the closed disposal facility for a certain period of time. Another example is the dependency of the waste inventory on whether spent fuel is reprocessed or not.

4.3.2. Siting and authorization for construction

Once a clear understanding has been obtained on what needs to be done and under what boundary conditions, the development of the disposal system can start. The ultimate goal of the system development is to obtain a licence to implement the disposal facility. This requires engineering and scientific work:

(a) To develop a safety strategy;
(b) To investigate possible sites and ultimately select a potential disposal site (or sites);
(c) To characterize the site;

[3] See https://nucleus.iaea.org/sites/connect/URFpublic/Pages/default.aspx

(d) To specify a design for disposal;
(e) To develop a safety case and environmental impact assessments.

The components of disposal development — safety strategy, design and engineering work, site characterization — and the dynamics of disposal system development that iteratively evolves from an initial, generic disposal system over multiple siting iterations to a concept and site supporting a licence application is described on the URF Network web site.[4]

The development of licence applications will be supported by needs driven RD&D providing the data and information for the engineering, natural environment and safety concept. Many science and engineering disciplines (e.g. geology, hydrogeology, chemistry, material sciences, nuclear, construction, mining engineering) will come into play. The development work will be compiled into milestone reports that form the technical basis for licence applications (for equipment certification, construction, operation, closure).

4.3.3. Ongoing science and engineering during project implementation

Finally, disposal system development can contain ongoing science and engineering during project implementation. This work is done:

(a) To maintain, update and confirm the safety case;
(b) To characterize further the underground site;
(c) To update technology;
(d) To adjust to evolving waste inventories.

While this follows the same iterative development as illustrated above, it serves the goal of verifying, evolving and improving the safety case and disposal system throughout the operational phase. It benefits from opportunities for continuous learning both from actual construction and operation experience — especially through monitoring. It also includes focused disposal system RD&D (e.g. to provide for improved or alternative construction methods or to modify specific components such as the waste disposal package or backfill material).

4.4. DISPOSAL IMPLEMENTATION

Disposal project implementation concerns the actual realization of the disposal project. It can be regarded as similar to any other industrial project, taking account of the particular safety aspects relating to nuclear facilities. The activities implementing the disposal programme can be broken down according to the following components in the disposal system:

— Non-nuclear surface facilities;
— Nuclear surface facilities;
— Waste transport to and waste transfer within the disposal facility;
— Disposal facilities;
— Access facilities to underground repository (only for geological disposal facilities).

A similar breakdown is proposed by the EDRAM group [13]. The activities relating to those facilities, equipment or infrastructure concern the following:

— Their detailed design and engineering to draw up the blueprints for building the facilities;
— Their purchase, construction (including outfitting them with the necessary technical equipment such as ventilation, water and electricity, telecommunications) and commissioning;
— Their operation, which includes inspection and maintenance and, if appropriate, modification;

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[4] See https://nucleus.iaea.org/sites/connect/URFpublic/Pages/default.aspx

— Their dismantling (including removal of the technical equipment) and decommissioning, and the remediation of the site.

These components are further described and detailed in Sections 4.4.1–4.4.5. These capture the main activities in the implementation of a disposal system and are presented in a sufficiently generic and abstract manner to be applicable to a wide range of disposal programmes. This by no means prescribes that these activities be included in a disposal programme. Rather, this generic description strives for a comprehensive coverage of possible activities to enable specific programmes to identify those that are relevant and those that can be excluded.

In addition to these components, it will be necessary to set up an on-site organization responsible for the operational management of the site and those activities that cannot be allocated to a specific facility. Examples of such activities are site security, site monitoring and support services such as human resources and IT.

For some activities, such as human resources, synergies might be found between the on-site organization and the WMO. It is up to the WMO to decide how the operational management of the disposal project implementation is to be organized. Regardless of how and by whom they are done, the activities listed under this component will need to be done and therefore need to be included in the cost estimate.

The USDOE Carlsbad Field Office at the WIPP facility is an example of an on-site organization. The functions and responsibilities of this organization are described in Ref. [38].

4.4.1. Non-nuclear surface facilities

Non-nuclear facilities consist of the site infrastructure and all facilities at the surface where no nuclear operations are performed and can comprise some of the following items or activity:

(a) Land purchase and landscaping;
(b) Site infrastructure and connecting it to existing infrastructure (roads and bridges, quays, railways, utilities such as water, electricity, gas, telecommunications, sewage, water treatment);
(c) Administration and office buildings, utility buildings, workshops and laboratories;
(d) Material production plants (concrete, buffer, backfill);
(e) Site security (fence, security posts, surveillance systems);
(f) Rock processing facilities and rock dumps;
(g) Communication and visitor centres.

4.4.2. Radiologically controlled surface facilities

Depending on the scope of the disposal programme, the radiologically controlled facilities may cover a wide range of waste activities (e.g. waste package receipt, waste inspection and acceptance, treatment or processing, storing, encapsulation). These activities may require the construction, operation and dismantling and decommissioning of the following types of nuclear facility:

(a) Waste reception or acceptance plant;
(b) Waste processing or treatment plant;
(c) Interim storage facilities or buffer facilities;
(d) Encapsulation plant.

These facilities will need to be equipped with waste transport and handling systems, and radiation protection systems, among other things as required.

4.4.3. Waste transport and transfer

Waste transport relates to the transport of the waste to the disposal site (i.e. to the facility where the waste is received on-site). Some disposal programmes might not consider this transport to be part of the disposal programme. They may consider it as a waste producer responsibility and may not include the costs associated with this transport in the disposal programme's cost.

Waste transfer encompasses all waste movements on-site. This includes waste transfers on surface, between the surface facilities, and waste transfer to and emplacement in the disposal facility.

4.4.4. Disposal facilities

The disposal facilities (underground for geological disposal and on surface for surface disposal) comprise the disposal cells, rooms, units, trenches or vaults and auxiliary facilities, for example for the maintenance or storage of equipment. A pilot facility may also be part of the disposal facilities. The outfitting of these facilities may include water and electricity, telecommunications, ventilation systems, fire protection and radiological protection equipment.

For surface disposal, the access routes are included in the disposal facilities as these are rather straightforward. This will often be the road between the encapsulation plant or buffer storage to the disposal facility. For geological disposal, the access facilities are covered by a separate WBS item (see Section 4.4.5). Closure of these facilities could include backfilling. The construction of underground facilities will require the removal of excavated rock.

4.4.5. Access facilities to underground repository

Access facilities to an underground repository include shafts and ramps and may also include the underground access routes that connect the disposal cells to the surface facilities (i.e. encapsulation plant or buffer storage facility). Rescue chambers might be foreseen as part of the access facilities. The access facilities need to be outfitted as well, and the shafts and ramps will be equipped with a hoisting system for transferring the waste from the surface to the underground repository.

Similar to the disposal facilities, the access facilities will be backfilled after completion of the waste disposal activities. These access facilities may be seen as part of the disposal facilities. However, they usually represent a high cost which needs to be paid for early in the programme's implementation. It might therefore be useful to have them as a separate cost item in the WBS.

5. COST ASSESSMENT OF THE WORK BREAKDOWN STRUCTURE

Once the activities of the disposal programme have been identified in the WBS, the costs associated with each WBS element are assessed to obtain an estimation of the overall overnight cost of the programme. This requires building a database including quantities or durations of the WBS items and their estimated unit costs. These unit costs can include labour costs, material costs, the cost of infrastructure works such as the building of roads and the cost of consumables such as electricity, water or fuel.

Some general considerations on the cost database are provided in Section 5.1, after which guidelines on developing a cost database specific to a waste disposal programme is given in Section 5.2. Again, in the approach followed here, uncertainties on the programme, the quantities or unit costs are ignored at this stage. These are addressed in the next stage (see Section 6).

5.1. COST DATABASE

The cost database gathers all quantities or durations and the estimated unit costs of the items in the WBS. The database forms the foundation of the estimate and its quality will determine that of the overall cost estimate. The following aspects require proper consideration when building and maintaining a reliable cost database:

(a) Historical data and mechanisms for updating or normalizing cost data;
(b) Categorization of cost items;

(c) Quality assurance and traceability.

The amount of data collected and the level of detail of the database will depend on the maturity of the programme and on the time and budget available for building the database. It might not be possible to accurately define the quantities and durations of the WBS items for a programme that is in an immature and very conceptual stage. As the programme develops and becomes more detailed, the cost database may become more specific and extensive as well.

5.1.1. Historical data and cost normalization

A cost database may be built based on historical data from similar projects or programmes, such as other disposal programmes. Possible data sources for disposal programmes are given in Section 5.2.

Other industrial experience can also provide useful cost information. The nuclear surface facilities are often similar to existing nuclear facilities, and tunnelling and mining work can guide cost estimation for repository construction and engineering. For example, the cost of constructing shafts and drifts can be assessed by contractors in the mining or tunnelling industry. It is, however, important to keep in mind the nuclear context in which the work is to be done. In such a context, experience shows that the costs typically associated with conventional industrial projects tend to increase significantly when the same activity is performed in a nuclear context. A mine is operated to extract valuable minerals, while the repository needs to safely operate for a long period of time. This can require specialized materials and equipment and extensive quality controls to ensure that the materials are of high integrity.

Vendors and contractors of equipment, materials or services may also be contacted to give cost estimates or prices. It is, however, crucial to check to what extent historical data is applicable and relevant. This requires that the scope and context of the data and any underlying assumptions are understood. Is a labour cost the cost of the direct labour, or does it include overhead costs? Do the labour costs apply to employees of the organization, or is it the cost of outsourced or contracted labour including profit? How old are the cost data and in what reference year are they expressed? Are the data actual project costs, or are they an estimate as well? In cases where they are actual costs, it may be important to verify whether the project has encountered particular problems. Some problems can be caused by weather delays, which might not apply to the project for which the cost is estimated.

Often, it will be necessary to adjust historical data to make them consistent or suitable for the cost estimate. This is called data normalization.

Older cost data will require updating to take account of cost inflation and escalation[5]. This can be done by applying an indexation mechanism. The indices are often published by higher authorities, such as federations representing certain industries. These indices measure the average rate of inflation for a particular market basket of goods. Different indices will be applied for labour rates and for material or equipment costs. It is therefore important to select an index that is representative for the cost item that is estimated.

Cost indexation is largely facilitated when the costs in the cost database are grouped into different categories distinguishing between labour, material, equipment and other costs which require using different indices. Possible cost categories are discussed in Section 5.1.2.

Unit costs may also be converted to a different currency or to different size units. Converting units is generally quite straightforward. Currency conversion of itself is also straightforward, but a currency conversion does not take account of differences in the purchasing power between countries. It might therefore be more useful to use the PPP exchange rates (from OECD.Stat[6]). These are rates of currency conversion that equalize the purchasing power of different currencies by eliminating the differences in price levels between countries. It might likewise be necessary to adjust for regional cost differences.

Cost adjustments might also be needed to take account of technology maturing, learning and rate effects. Costs usually depend on quantity. When more items are produced or delivered, their unit costs generally decrease. Productivity will usually improve over time due technological advancements and increased staff or worker experience with the tasks at hand. Taking account of such effects can be difficult and is often subjective. Best

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[5] Cost escalation is the change in the cost of specific goods or services over time. It includes the effects of inflation, but it also takes account of cost changes due to changes in technology and in supply or demand.

[6] See http://stats.oecd.org

practice therefore is to clearly highlight where technological improvements or increased productivity are assumed and to provide a justification for why such improvements are anticipated.

Quantities or durations might need to be scaled to take account of differences in size. When scaling data, it is important to know which part of the cost is not affected by a difference in size or quantity and which part is. When an underground repository doubles in size, the cost will increase, but it might not be necessary to have twice as many access routes such as shafts or ramps. Consequently, the cost of the extended repository will likely not double.

Finally, it will also be important to evaluate the need to include allowances. Allowances often refers to an experience based percentage that is added to the cost of an item to take account of the cost of items that are unspecified when insufficient information is available to develop a detailed WBS of the programme. Allowances are typically used for items such as furnishing, telecommunications and utilities, and should not be confused with contingencies, which are provisions added to an estimate to allow for additional costs that experience shows will likely be required. Contingencies relate to cost uncertainties as well as to risks, which are discussed in Section 6.

Finally, when normalizing or adapting data, cost estimators should be aware of optimism bias and the tendency to be over optimistic. The Green Book [30] explicitly requires that estimators adjust for optimism bias when appraising projects and programmes in the United Kingdom, and the USGAO advises not to remove inefficiencies from historical cost data, as most programmes or projects encounter problems and inefficiencies [33]. Taking account of optimism bias is related to identifying risks and uncertainties, and incorporating them into the cost estimate using allowances and contingencies (see Section 6).

5.1.2. Cost categories

It is useful to group costs into categories to help to understand their impact on the overall cost estimate and to adjust or update the estimate. Different cost categories, such as labour or material costs, will usually require different indices, and scaling cost data to take account of differences in size or quantity often requires making a distinction between fixed and variable costs. Costs can be categorized in different ways. Four typical cost categories are:

(a) Labour costs: Employee labour rates including fringe benefits, contributions to social security, health insurance and pension scheme and overhead costs.
(b) Investment costs: Equipment and material costs.
(c) Expenses: Various costs that cannot be identified as labour or investment costs, such as consumables, utility costs, supplies, spare parts, insurance and taxes.
(d) Contingencies: Provisions for costs that are likely to occur within the defined project, but that cannot be known in advance, such as costs relating to equipment breakdown, bad weather delays and strikes (see Section 6).

Another useful distinction is the one between fixed and variable costs. In the context of a waste disposal programme, fixed costs can be defined as (largely) independent of the amount of waste. The cost of the safety assessment will generally not be affected when the amount of waste increases. Variable costs are those that do depend on and are sometimes (largely) proportional to the amount of waste. The cost of encapsulating the waste before disposal will of course increase when more waste needs to be encapsulated.

Some costs can be defined as step fixed costs. These are costs that are independent of the amount of waste up to a certain point. In cases of geological disposal, the costs of the transfer routes to the underground repository will not immediately be affected when the amount of waste increases. But at a given level of increase in waste the extension of the repository might require extra access routes. The cost of the repository access routes can therefore be considered as a step fixed cost.

Categorizing the costs into fixed, variable and step fixed costs will facilitate adapting the overall cost estimate when the amount of waste changes.

5.1.3. Quality assurance and traceability

Finally, quality assurance and traceability of data need to be guaranteed by implementing proper data management tools and systems. It will, for example, be crucial to record and keep track of the sources for the cost data and document how the cost data are adapted, scaled or indexed and which assumptions might be made when using or adapting the cost data. Future cost estimates will benefit from such records.

Furthermore, it will be important to get the cost database and the overall cost estimate reviewed by external experts to check the validity and credibility of the estimate.

More guidance on ensuring the development of high quality and reliable cost estimates can be found in the cost estimating guide published by the USGAO [33]. A 2016 report by the UK National Audit Office describes a systematic approach for auditing estimates [39].

5.2. DATA SOURCES AND COST EXAMPLES OF A WASTE DISPOSAL PROGRAMME

Sections 5.2.1–5.2.4 provide possibly relevant data sources and cost examples for the elements of the WBS. Specific cost examples are given in tables. All costs are approximate figures expressed in US dollars. Costs in other currencies are converted using PPP, with conversion factors given in the Annex.

It should be emphasized that the examples and figures given are to be used with caution. For a proper understanding of these figures, more context and explanation (such as the reference year and the scope of the costs, whether they are discounted or undiscounted costs and whether contingencies are included or not) are needed than are given here. More information about the given figures can be found in the references given.

The examples are only meant to provide a range of orders of magnitude and give an idea of the main cost drivers or components of a disposal programme. The purpose is not to compare costs between different programmes. Comparing the costs of different disposal programmes is also often not very relevant or helpful, as many factors, such as the waste inventory, the specific design and the timing of the programme, make cost comparisons meaningless. Moreover, in addition to these factors, currency exchange rates and differing inflation rates would complicate the comparisons. Different organizations also have different tasks, structures and different national contexts; and labour rates and prices often differ.

5.2.1. Disposal programme management

The costs of disposal programme management concern the costs of running the WMO. These will be mainly labour costs, including overhead costs of offices, utilities and equipment. Estimating this requires drawing up an organization chart to determine which functions are needed and how many people are to be employed to fulfil these functions. By assigning a labour cost to these functions, the cost of the WMO can be calculated. The workforce will likely vary over the lifetime of the disposal programme. It is therefore useful to identify which functions are needed at which stage in the disposal programme and to calculate the annual costs of the WMO over the disposal programme's lifetime.

Developing and implementing a disposal programme requires a wide range of highly specialized expertise. Some types of expertise are only needed for a short period of time, while others may be required for the complete duration of the disposal programme. The WMO will have to decide which expertise will be offered in house, by its own staff, and which will be outsourced. These decisions will make part of the WMO's commercial strategy, which is discussed in Section 6 as part of the risk management relating to the disposal programme.

It can be difficult to define the future functions that will be needed over the long timescales of a disposal programme. This can be further complicated when the organization has larger responsibilities than developing a disposal programme (e.g. decommissioning). In that case, only a part of the organization's efforts and costs would be allocated to the disposal programme. The organization charts of other WMOs can be used as a guide. Medium sized to large organizations can also serve as examples of the general functions that typically occur in such organizations.

When looking for a WMO that can serve as a guidance tool, it is important to check to what extent the scope and structure of that WMO is comparable or representative, as there are significant differences in how different WMOs manage the disposal programme. Some WMOs have much expertise in house to develop and implement a disposal programme, while others prefer to perform the project management tasks and outsource many of the more specific tasks.

Drawing up an organization chart based on a WMO is probably more useful than benchmarking. The usefulness of comparing generic management costs is limited because:

(a) Different organizations have different tasks, are differently structured and have a different national context (inventory, nuclear policy and strategy, legal framework);
(b) Labour rates and prices often differ and conversion is not always straightforward;
(c) Costs for management and support functions may be called out explicitly or included in other elements (e.g. other organizations might allocate the costs of its engineers and scientists to their RD&D costs, rather than the cost of managing the disposal programme).

Assessing the labour costs can be done using historical labour costs for similar functions. It will be important to acknowledge the unique context or specificity of the project. In the case of nuclear projects, there is often a need for highly skilled workers, whose labour rates tend to exceed national and regional averages (see Table 1).

TABLE 1. EXAMPLES OF ANNUAL COSTS AND ESTIMATED FUTURE COSTS OF RUNNING WMOs

	Running costs
Belgium [40]	The Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS) is responsible for managing waste, including waste acceptance, storage and disposal. Decommissioning is not a task for ONDRAF/NIRAS. This responsibility lies with the operators of facilities. In 2015, the ONDRAF/NIRAS had 122 employees and an annual turnover of US $155 million.
Canada [41]	The Nuclear Waste Management Organization (NWMO) estimated in 2016 the total cost of managing, siting, developing and implementing a spent fuel repository at US $14 billion, of which US $742 million, around 5%, could be attributed to programme management.
Czech Republic [42]	The Radioactive Waste Repository Authority (SÚRAO) is responsible for the operation of LLW and ILW repositories, and for the development and implementation of geological disposal facilities for HLW and spent fuel. It had an annual budget of US $25 million in 2015 and employed 53 people.
Finland [43]	Posiva was founded in 1995 by two Finnish nuclear plant owners to develop and implement a spent fuel disposal facility. At the end of 2016, it employed 79 people and had an annual turnover of $69 million.
France [44]	The National Radioactive Waste Management Agency (Andra) is in charge of the long term management of radioactive waste in France. In 2016, it had an annual turnover of US $280 million. Approximately 650 employees worked for Andra at the end of 2017.
Japan	The Nuclear Waste Management Organization of Japan (NUMO) is responsible for the geological disposal programme for ILW and HLW from the Japanese nuclear fuel cycle. Approximately 130 people were working for NUMO as of April 2017. NUMO's annual budgets for the fiscal years 2015, 2016 and 2017 were, respectively, US $74 million, US $88 million and US $95 million. NUMO estimates the future cost of managing a geological disposal project at US $5.9 billion, or 14% of the total cost of US $41 billion for implementing the disposal project.
Slovakia [45]	The Nuclear and Decommissioning Company (JAVYS) is a state entity responsible for the decommissioning of two nuclear power plants and manages all waste management and spent fuel management in Slovakia. In 2015, 819 people were working for JAVYS and its annual turnover was US $150 million (including funding received from the National Nuclear Fund and the Bohunice International Decommissioning Fund).
Slovenia [46]	The Agency for Radwaste Management (ARAO) is responsible for the long term management of spent fuel and radioactive waste. In 2016, it had 20 employees.

TABLE 1. EXAMPLES OF ANNUAL COSTS AND ESTIMATED FUTURE COSTS OF RUNNING WMOs (cont.)

	Running costs
Sweden*	Swedish nuclear power companies have formed a jointly owned company, SKB, to manage and dispose of radioactive waste. SKB employs a staff of nearly 600 people. When external experts are included, just over 800 people are involved in the radioactive waste disposal programme.
United Kingdom [47]	Radioactive Waste Management Ltd (RWM) is a subsidiary of the Nuclear Decommissioning Authority (NDA). The NDA is responsible for the decommissioning and radioactive waste management of 17 legacy sites in the United Kingdom. RWM's task is to deliver a geological disposal facility (GDF). In 2018, RWM employed around 150 people and had a total annual budget of US $37 million.

Note: The annual budgets given often include budgets for external services, such as RD&D and public relations, and are therefore not completely representative of the costs of running a WMO as presented in this publication. Nevertheless, the figures reflect the differences in WMO size, and the extent and maturity of their disposal programmes. Some WMOs also have larger responsibilities than disposal. In several cases, they are in charge of decommissioning as well. In those cases, only a certain fraction of the cost of running the WMO is to be assigned to the disposal programme.

* www.skb.com/about-skb/organisation

5.2.2. Stakeholder involvement

Stakeholder involvement generally entails running workshops, communication campaigns and information and consultation events, holding public debates or hearings, conducting sociopolitical research, publishing newsletters, operating an information centre and providing financial incentives or potential benefits for local communities (see Table 2).

TABLE 2. EXAMPLES OF ACTIVITIES AND COSTS FOR STAKEHOLDER INVOLVEMENT ACTIVITIES

	Activities and costs
Belgium	The annual budget for communication of ONDRAF/NIRAS amounted to US $2 million in 2017. This included communication on the surface disposal project and on the programme of geological disposal, and the running of an information centre about the management of radioactive waste in Belgium.
Bulgaria	The annual cost of public relations amounts to US $50 000 (excluding staff salaries). There is also an information centre at the Kozloduy nuclear power plant. This centre is run by State Enterprise Radioactive Waste (SERAW) from its budget. Furthermore, a festival is organized every year to inform and involve the public in the waste management plans.
Canada [41]	The NWMO estimated in 2016 the cost of stakeholder involvement to be US $720 million, or 5% of the total cost of its geological disposal programme. These are the involvement costs up to the point of receiving the licence for disposal. Stakeholder involvement will continue after that.
Czech Republic	By 2016, SÚRAO spent US $1 million on public relations, such as advertisements in newspapers, brochures and meetings. In addition, SÚRAO operates information centres at the three current disposal repository locations (Richard, Bratrství, Dukovany) and its headquarters, in Prague.

TABLE 2. EXAMPLES OF ACTIVITIES AND COSTS FOR STAKEHOLDER INVOLVEMENT ACTIVITIES (cont.)

	Activities and costs
Finland [11]	Posiva hires local officers to help to promote communication and to create an exchange with nearby communities. The activities consist of events and seminars for public audiences and companies, and debates with residents.
France	Laws passed in 1991 and 2006 require public involvement in the disposal programme and the Commission Locale d'Information is responsible for providing information to the local community. This organization is funded by the Government and waste producers directly and its budget is US $375 000. To accompany the project for HLW and ILW disposal, two public debates were organized, one in 2005 and the other in 2013, in accordance with the law that describes how these debates have to be organized and calling on the National Commission for Public Debate.
Japan	NUMO has spent US $240 million over the last 15 years on stakeholder involvement (excluding staff salaries). This expenditure includes communication campaigns, such as holding symposia, publishing newsletters, media coverage such as TV and newspapers, creating web pages and social network sites, and operating exhibition vehicles. These activities are not site specific. The expenditure does not include community benefits or communication centres.
Slovakia	In 2015, JAVYS spent US $150 000 on public relations activities and direct sponsoring of local municipalities and local activities. In addition, JAVYS operates an information centre at the Bohunice site and commenced the operation of a new information centre at the National Radioactive Waste Repository, in Mochovce, in December 2015.
Sweden [48]	Municipalities where there have been site investigations for a disposal facility for spent fuel, or where such a disposal facility is planned or being built, are entitled to compensation for the cost of disseminating information to the public. Disbursements may be set at no more than US $1 million per municipality and 12 month period. The municipalities of Östhammar and Oskarshamn have received such disbursements. Non-profit organizations involved in site evaluation, and with at least 1000 members, can apply for financing. A total of US $600 000 may be provided per calendar year.

Note: Most disposal programmes have an annual communication budget in the order of hundreds of thousands to millions of US dollars. The NWMO (Canada) and NUMO (Japan) estimate the cost of engaging with local communities and the public at large to be several hundred million US dollars.

It is becoming common in countries where disposal facilities are being developed or implemented to offer incentives and benefits to communities involved in a site selection process or the implementation of a disposal facility (see Table 3). Incentives and benefits to local communities can be offered in the form of direct payments, infrastructure and socioeconomic development, and support for local activities. The level of benefits may be dependent on the phase in question. Reference [21] provides a more comprehensive and detailed description of the different types of incentive that can be applied. Reference [52] describes benchmarking of community benefits relating to radioactive waste management facilities and contains several specific examples of community benefits.

Finally, payments to the regulator for the licensing process of the disposal facility are assumed here to be part of the costs of managing the disposal programme (see Table 4). The regulator can be supported by annual payments, such as in Bulgaria and Canada, or by payments linked to the licensing procedures, as is the case in Belgium and the Netherlands. Sometimes a combination of both schemes is applied. The payment to the regulator in the Czech Republic is such an example. In addition to the regulator, other authorities may be included in the decision making process of the disposal programme as well. It is important to identify the authorities involved and the permits that might need to be obtained for implementing the disposal programme. Subsequently, it needs to be checked whether any payments need to be made for engaging these authorities or obtaining these permits.

TABLE 3. EXAMPLES OF BENEFITS OR INCENTIVES TO LOCAL COMMUNITIES

	Benefits/incentives
Belgium [49, 50]	ONDRAF/NIRAS has established a medium term fund valued at US $160 million to organize a participative process and provide societal support. A part of this amount goes into a trust fund for future generations of the local community as part of the agreement to site its LLW and ILW surface disposal facility.
Bulgaria	The law prescribes that incentives are paid to local communities, and that the summary cost of the approved projects be no more than 2% of the annual budget of SERAW. Each year, US $225 000 is paid for societal incentives to the municipalities of Kozloduy and Novi-Han hosting waste management facilities. These communities can invest the money in projects such as infrastructure, kindergartens, schools, parks and other activities that are socially significant or beneficial.
Canada [51]	The NWMO introduced the Acknowledging Early Aboriginal Participation programme, complementing an earlier programme for communities involved in the site selection process. Communities that had participated in that earlier programme were eligible to receive US $190 000 to support their sustainability and well being. Eight communities accepted funding in 2015.
Czech Republic [42]	SÚRAO paid a total of US $5.5 million in 2015 to the local communities of the seven areas involved in site investigations for the geological disposal of radioactive waste. A further US $923 000 was paid that year to communities in the area of the LLW or ILW repository.
Finland [52, 53]	Upon receiving the agreement of the Eurajoki community for the development of the Onkalo research facility, Posiva moved a large part of its headquarters (80 employees) to the community and signed a lease for a mansion from the municipality. Under the terms of the lease, the mansion will be renovated for its new use; and since it was formerly a retirement home, Posiva lent the municipality US $9 million for the construction of a new home. Posiva also predicted that the implementation of the disposal project would create between 100 and 200 jobs, depending on the phase the disposal project is in.
France	Andra was initially involved in economic development support around the Bure site. This approach was curtailed in 2006 and the corresponding law on radioactive waste management describes the economic support mechanism that is financed by the Government. The financing of projects locally is based on a zoning system in the Meuse and Haute Marne districts. Municipalities closer to the site are advantaged.
Japan	Communities can volunteer to be host communities for a GDF. Up to US $11 million per year at the stage of the literature survey can be paid as an incentive to every volunteering community by the Government in line with the related law. The site selection and characterization procedure comprises three stages: literature survey, surface investigation and underground investigation. The financial incentives will increase as the site selection procedure progresses. At the end of each stage, a community has the possibility to withdraw its candidature.
Republic of Korea [54]	Korea Hydro & Nuclear Power Company, the nuclear power plant operator, has paid financial support of US $340 million to the Gyeongju host community, which had decided to accept the construction of a disposal facility for LLW and ILW, and relocated its headquarters to the host community.
Sweden [55]	US $220 million was made available for providing added value to the communities of Oskarshamn and Östhammar involved in the site selection process for the deep geological repository for HLW. The programme looks at developing the regional economy and empowering local communities to build their own expertise. This amount did not come from the waste fund but was paid directly by the waste producers.

TABLE 3. EXAMPLES OF BENEFITS OR INCENTIVES TO LOCAL COMMUNITIES (cont.)

	Benefits/incentives
United Kingdom [56, 57]	The Copeland Community Fund is a fund open to community and voluntary organizations and non-profit bodies from the community hosting an LLW repository near Drigg, in Cumbria. On top of an initial endowment of US $14 million, US $2 million is paid into the fund for every year the facility receives waste. LLW from the decommissioning of Dounreay is disposed of in an LLW disposal facility adjacent to the site. The facility currently consists of two below surface disposal vaults. The NDA committed to pay US $5.7 million to the Caithness & North Sutherland Fund for projects to help to regenerate the area's economy. US $1.4 million was paid at the start of construction of the facility and US $430 000 per year will be paid for the first ten years of operation.
United States of America [58, 59]	Since 1983, US $530 million has been invested in financial and technical assistance to the State of Nevada, local counties and educational institutions for conducting oversight and monitoring activities. Waste Control Specialists (WCS), the private company operating the LLW repository in Andrews County, Texas, has more than 170 full time employees with an annual payroll of more than US $13 million. In addition, 5% of WCS receipts go to the county. This amount is expected to be US $3 million per year.

Note: Community benefits or incentives can vary significantly and can range from relatively small sums for empowering communities to several hundred million US dollars.

TABLE 4. EXAMPLES OF REGULATOR COSTS

	Regulator costs
Bulgaria [60]	The fees that the Bulgarian Nuclear Regulatory Agency can collect with regard to licences are strictly defined. The fee for an initial licence for a radioactive waste management facility for ILW is set at US $500 000. The annual fee for following up on the licence and periodically assessing the nuclear safety and radiation protection of the facility amounts to US $640 000.
Canada [41]	The NWMO has estimated the licensing costs of a spent fuel repository at US $530 million, or 4% of the total cost. This cost does not cover regulatory fees, but includes NWMO licensing support staffing and activities.
Netherlands [61]	Fees need to be paid to the regulator when applying for a construction, operation and dismantle and decommission licence, as well as when the licence is granted. These fees are set by law and are in the order of tens or hundreds of thousands of US dollars. The annual licence cost amounts to US $223 000.
Slovakia	According to legislation, each owner of a nuclear facility or licence holder is liable to make an annual payment to the regulator. In 2015, JAVYS paid the Nuclear Safety Authority US $216 000 for the treatment of radioactive waste and US $63 000 for the operation of the National Radioactive Waste Repository, in Mochovce. Standard fees are paid to the Ministry of Health and Ministry of Environment within the licensing approval procedure.
United States of America [58]	The Nuclear Regulatory Commission received a total of US $580 million from the USDOE for its involvement in the Yucca Mountain project in 1983–2010. This represents 4% of the total investment that was made in the project during that period.

Note: In several countries, the regulatory body receives annual payments from the WMO. In addition, fees are usually paid during the licence procedure. These fees are generally in the order of hundreds of thousands of US dollars.

5.2.3. Disposal system development

The development of a disposal system requires RD&D efforts that are often extensive. Assessing the cost of the RD&D needed for disposal system development will start by developing the requirements the disposal system has to meet, and understanding how RD&D can develop solutions to achieve these.

Personnel costs are usually the largest RD&D cost. As explained in Section 5.2.1, WMOs can have much expertise in house. In such cases, much of the disposal system development is done by the WMO's scientists and engineers, which means that many of the costs of disposal system development will be allocated to disposal programme management. Other WMOs might outsource most of that work to external companies and experts.

Other RD&D costs include equipment costs, such as hardware and software to perform numerical simulations and modelling work. It might also be necessary to develop specialized software. The required RD&D efforts can vary significantly depending on the following factors:

(a) The uniqueness of the disposal programme, or the extent to which it can rely on or transfer available knowledge from already existing programmes;
(b) The availability of relevant knowledge in the public domain;
(c) The required level of geological investigation for site screening and characterization;
(d) The number of candidate sites to investigate;
(e) The iterative nature of cycling through an RD&D phase, updating the safety assessment, verifying to what extent requirements are met, understanding additional requirements and refining existing ones, and then developing the programme for the next RD&D cycle.

For some aspects or items of the disposal system development (e.g. large scale experiments or mock-up tests, site investigation or characterization, site selection and monitoring), examples or case studies can give an idea of the magnitude of cost to be expected (see Table 5).

TABLE 5. EXAMPLES OF RD&D COSTS

	RD&D costs
Belgium [62]	The total RD&D cost of geological disposal, including the cost of the underground laboratory High Activity Disposal Experimental Site (HADES) for 1974–2014 is estimated at US $450 million, which is US $15 million per year.
Bulgaria	SERAW's annual budget for RD&D on developing a GDF amounted in 2016 to US $625 000. SERAW's programme on geological disposal is a very preliminary one which remains to be approved by the Government. Based on a literature study of international cost figures, SERAW estimated the cost of developing the facility at US $800 million, before starting the repository construction in 2070. This estimated cost includes site investigation, characterization and preparation, the construction and operation of the URL at the selected site, and the development of the safety analysis and technical design.
Canada [41]	NWMO estimated the cost of developing a spent fuel repository to be US $1.3 billion.
China	The siting process for an HLW GDF started in the 1980s. After comparison of six potential regions, the Beishan area, located in north-west China, was considered to be the most favourable. RD&D has been undertaken on the development of a conceptual design, buffer material and radionuclide migration, and safety case studies have been conducted. US $98 million has been spent on RD&D relating to the geological disposal programme.
France [63]	In 2014, Andra received more than US $250 million per year for RD&D and design studies for its geological disposal programme.
Germany [64]	The Konrad mine, an abandoned iron ore mine, is currently being converted to an underground disposal facility for radioactive waste with negligible heat generation. The costs of planning and exploration of the facility from 1977 to the end of 2007 amounted to approximately US $1.2 billion.

TABLE 5. EXAMPLES OF RD&D COSTS (cont.)

	RD&D costs
Japan	NUMO has spent US $130 million on RD&D and has an annual budget of US $10 million for externally contracted RD&D. NUMO estimates that US $2.3 billion and US $3.6 billion will be spent on RD&D and on-site characterization and land cost, respectively. This estimate assumes that ten candidate sites need to be investigated based on a literature survey, five sites based on a preliminary investigation and one based on a detailed investigation, and includes US $580 million for the construction of a URL at the site.
Slovakia	JAVYS is appointed to coordinate the activities for the preparation of a GDF of spent fuel and long lived ILW. The 2018–2020 RD&D budget for this facility is US $5.6 million.
Sweden [35]	The cost of RD&D to develop a spent fuel repository, including operating the Äspö URL, and for siting and designing the spent fuel repository was a total of US $1.5 billion as of 2017.
United States of America [65]	The costs of repository development and evaluation from 1983 to 2006 amounted US $8 billion. This includes all of the expenses associated with evaluating various geological formations in the 1980s, and with the conceptual design and site characterization activities for the Yucca Mountain project since 1987, when Congress decided to focus further work only on Yucca Mountain.

Note: In the examples, the spent or estimated budgets for developing a disposal programme are in the order of tens or hundreds of millions of US dollars, or in some cases even billions of US dollars (for Japan and the United States of America). The cost of developing a disposal programme will be affected by the extent to which proven technology can be used. Using a disposal concept that has already been developed will reduce the cost of further developing this concept compared to developing a first-of-a-kind disposal concept. The El Cabril LLW repository, in Spain, is similar to the LLW repository of the Centre de l'Aube, in France. SKB and Posiva have a very similar disposal concept and were able to share some of the RD&D costs.

Some geological disposal programmes have constructed and operated an underground research facility to support their disposal system development. Other programmes plan to construct a URL as part of an underground disposal facility (see Table 6).

TABLE 6. EXAMPLES OF COST OF CONSTRUCTING AND OPERATING A URL

	Constructing and operating costs
China	Construction of a URL is planned for around 2020. The estimated cost of the URL and RD&D activities during construction is US $470 million.
France	The Bure URL is built in argillaceous rock at a depth of 500 m. The laboratory has been in operation for experiments since early 2000. Its total construction cost to date amounts to US $254 million. The yearly cost of operating the URL and running experiments was US $28 million in 2017.
Japan	Japan has two URLs: the Horonobe URL at a depth of 350 m in sedimentary rock and the Mizunami URL at a depth of 500 m in crystalline rock. The total cost of the Horonobe URL was US $480 million from 1996 to 2016. The cost of the Mizunami URL was approximately US $530 million from 1996 to 2016.
Republic of Korea [66]	The KURT is 120 m deep in granite rock and is located in a mountainous area. It has a total length of 550 m. Its construction cost was about US $12 million.
Sweden	The Äspö URL is a 460 m deep URL in crystalline rock. The construction costs between 1990 and 1995 were US $50 million including investigations during construction. The total facility cost up to 2015 amounted to US $165 million. The average annual operation cost is US $3 million.

TABLE 6. EXAMPLES OF COST OF CONSTRUCTING AND OPERATING A URL (cont.)

	Constructing and operating costs
Switzerland	Switzerland has two URLs: the Mont Terri URL in argillaceous rock and the Grimsel URL in crystalline rock. The Grimsel Test Site is located in the Swiss Alps and was established in 1984 as an URL supporting a wide range of research projects on the geological disposal of radioactive waste. The Mont Terri laboratory has been operated since 1996. It is accessed via the safety gallery of a motorway tunnel. In the period between 1996 and mid-2016 US $90 million was invested (total investment consists of costs arising from the research programme and the operation of the rock laboratory). In that period, a total of 149 experiments were initiated, of which 99 have been completed and 50 are still in progress. An average annual budget for research and operation amounts to US $4 million.

Note: Some URLs are generic, such as Horonobe (Japan) and Äspö (Sweden), while others are site specific, such as Onkalo (Finland) and Bure (France). URL construction costs vary from US $12 million (KAERI Underground Research Tunnel (KURT), Republic of Korea) to US $254 million (Bure, France). The differences are mainly determined by the type of host rock, the depth and the extent of the laboratory. The KURT URL is only 120 m deep and has a total length of 550 m, while the Bure URL, at a depth of 500 m, has several kilometres of galleries, microtunnels and boreholes. Operating costs usually are in the order of millions to tens of millions of US dollars.

5.2.4. Disposal implementation

Disposal implementation concerns the realization of the project, which has similar characteristics to conventional large scale industrial projects. Assessing the costs of implementing industrial projects has been done many times. Examples of disposal facilities are however limited. Worldwide, various surface disposal facilities have been constructed and operated, but experience with closing such facilities is lacking (see Table 7). A few examples of geological disposal for LLW and ILW exist, but to date, no GDF for HLW and/or spent fuel has been fully developed (see Table 8).

TABLE 7. EXAMPLES OF NEAR SURFACE DISPOSAL PROJECT COSTS

	Project costs
France	Since 2000, yearly investment has been between US $600 000 and US $2.5 million. The annual operational cost is around US $50 million. The total cost of surveillance for the Centre de l'Aube over the 300 year period after closure is of the order of US $458 million (with a 3.5% discount rate and under 2016 economic conditions).
Romania [67]	There are currently two operating Canada deuterium–uranium (CANDU) reactor units in Romania, both at the Cernavoda site. There are plans to commission another two CANDU reactor units at that site. To dispose of short lived LLW and ILW, a surface disposal facility is planned within the Cernavoda exclusion zone. The concept is based on the Centre de l'Aube facility, in France. It is anticipated that waste disposal operations will start in around 2021. The estimated cost of the facility is US $300 million assuming the operation of two CANDU reactor units, and US $600 million assuming the operation of four units.
Slovakia	The National Radioactive Waste Repository, in Mochovce, has been in operation since 2001. It is a surface type repository for the disposal of LLW and VLLW, built in the form of double rows. Two double rows with a total capacity of 7200 concrete containers are operational, and the construction of a third is planned for in the future. The designed capacity for the disposal of VLLW is 68 000 m^3 and the facility is to be built in three stages. The first stage of this has been in operation since 2016 and has a capacity of 20 000 m^3. The total construction cost of the third double row for LLW and the first stage for the disposal of the VLLW is US $27 million.

TABLE 7. EXAMPLES OF NEAR SURFACE DISPOSAL PROJECT COSTS (cont.)

	Project costs
Slovenia [68, 69]	ARAO plans to have a near surface silo type waste repository constructed by 2021. Under the baseline scenario, the repository is to accommodate the Slovenian half of the LLW and ILW from the Krško nuclear power plant and the entire Slovenian portion of institutional LLW and ILW. In this scenario, two operation phases are foreseen: one from 2022 to 2024 and one from 2050 to 2061. The facility is idle in the phase in between. The cost of construction and equipment with closure of the waste repository for the baseline scenario was estimated at US $50 million. In the case where this repository is constructed in cooperation with Croatia (the repository is also to accommodate the Croatian half of the LLW and ILW from the Krško nuclear power plant), the cost was estimated at US $63 million. In the case of a shared solution, the latter cost is expected to be divided between Slovenia and Croatia.
South Africa [70]	The Vaalputs trench type disposal facility for LLW (see Fig. 1, Section 2.3) has been in operation since 1986. In 2009 the site was transferred to the South African Nuclear Energy Corporation (Necsa). The facility will operate until 2034, when an institutional control period of 300 years starts. All costs until 2009 were directly paid by the South African Government. Cost details for this period were not found. The life cycle costs from 2009 onwards, including the institutional control phase, are estimated to be US $500 million.
United Kingdom [71]	The national LLW Repository facility near the village of Drigg has been in operation since 1959. The NDA took over the site in 2005. The future liability for this facility, including its operation and closure, is estimated at US $1.4 billion.

Note: The costs of implementing a surface disposal facility range from tens of millions to more than a billion US dollars.

TABLE 8. EXAMPLES OF GEOLOGICAL DISPOSAL PROJECT COSTS

	Project costs
Australia [72, 73]	In 2015, a commission was established by the South Australian Government to investigate the potential for increasing South Australia's participation in the nuclear fuel cycle. A part of this investigation concerned a possible disposal facility for spent fuel and ILW that is temporarily stored in storage facilities around the world. The overall facility includes a GDF for spent fuel and ILW, an LLW disposal facility on surface and an interim storage facility. Assuming that the facility receives 138 000 t HM of spent fuel and 390 000 m^3 of ILW, its total life cycle cost is estimated at US $97 billion.
Canada [41]	The cost of constructing, operating, closing and monitoring a spent fuel repository was estimated by NWMO to be around US $12 billion.
Czech Republic [74]	SÚRAO plans to dispose of its spent fuel and intermediate level LLW in a repository in granite at a depth of 500 m. The repository construction is foreseen for 2050–2065 and the disposal operations are expected to start in 2065. The current cost estimate for constructing and operating the repository, including RD&D, amounts US $8.6 billion.
Finland [75]	Posiva obtained a licence in 2016 to construct the spent fuel GDF at Olkiluoto. The disposal facility is located in a crystalline rock at a depth of 400–450 m. The estimated cost of constructing, operating and closing the facility amounts to US $4.5 billion.
France	The cost of Cigéo was set by the minister of ecology, sustainable development and energy on 20 January 2016 by ministerial ruling at a value of US $31 billion. The Cigéo project consists of the construction, operation and closure of a 500 m disposal facility for HLW and long lived ILW in an argillaceous host rock.

TABLE 8. EXAMPLES OF GEOLOGICAL DISPOSAL PROJECT COSTS (cont.)

	Project costs
Germany [64]	The costs incurred to date for planning and exploration, and the projected costs of construction, emplacement operation and closure for the Konrad disposal facility for radioactive waste with negligible heat generation are in the region of US $9.4 billion. This includes the US $1.2 billion that were spent between 1977 and 2007 on planning and exploration (see Section 5.2.3). The cost of the construction phase, between 2008 and 2022, is a total of US $3.6 billion. During the operational phase, the annual operating costs are currently estimated at US $100 million. The closure costs have been estimated at 10% of the total cost of building the disposal facility (i.e. US $363 million). The cost of the Morsleben disposal facility, a former potash and rock salt mine converted to a disposal facility for LLW and ILW, is estimated at US $3 billion. This includes a total cost of US $1.5 billion from 1990 to 2015. The remaining operating and closure costs have been provisionally estimated at US $1.2 billion. The total costs of building, operating and decommissioning a future disposal facility for heat generating radioactive waste is therefore estimated at approximately US $8.8 billion. A site for this facility has yet to be selected.
Hungary	The cost of constructing and operating the Bátaapáti LLW repository is estimated at US $1 billion. This includes the cost of site selection and an operation cost of US $7 million per year. The repository operation started in 2012 and is expected to go on until 2080. The cost of the closure of the repository and institutional control is estimated at US $162 million.
Japan	Japan considered 11 cases of deep geological disposal of its HLW and long lived LLW (some types of transuranic waste). In the end, two standard cases were selected: one in a crystalline host rock at a depth of 1000 m and one in a sedimentary host rock at a depth of 500 m. For both cases the cost was estimated, arriving at mean value of US $22 billion for implementing the disposal facility.
Romania [67]	The geological disposal concept for spent fuel and long lived waste is based on the Canadian geological repository for spent CANDU fuel. The cost of the facility was estimated at US $1 billion assuming the operation of two CANDU reactor units and US $2 billion assuming the operation of four units.
Sweden [35]	The cost of implementing the SKB spent fuel repository is estimated to be US $8 billion. This is not purely the cost of implementing the disposal project, as it also includes the costs of running SKB, communication costs, RD&D, transport of canisters and encapsulation of spent fuel in canisters. The figure includes both spent and future costs.
Switzerland [36]	The future cost estimated for the disposal of waste is US $8 billion. This includes the cost of covering uncertainties, as well as the cost of hazards and opportunities.
United Kingdom [76]	In its geological disposal cost estimate, the NDA has assumed a 650 m deep GDF in a higher strength host rock in which LLW, ILW, HLW and spent fuel can be co-located. The overnight lifetime cost is estimated at US $17 billion. This does not include the costs of any post-closure monitoring during institutional control, as these will be the responsibility of the authority charged with that control. This estimate includes siting, research, design, construction, operation and closure of a disposal facility. The estimated overnight cost up to the time at which first waste is emplaced in a GDF for LLW, ILW, HLW and spent fuel (which is assumed to be around 2040) is about US $6 billion. The cost excludes some significant activities, in particular the costs of waste encapsulation and of transport of waste to the GDF, which are the responsibility of the waste producer.
United States of America [65]	A total life cycle cost analysis of the Yucca Mountain project was made in 2008. The estimate includes the cost of research, construction and operation for the Yucca Mountain project from the beginning of the programme in 1983 to its closure and decommissioning in 2133. The total cost was estimated at US $96 billion. This includes the cost of activities that are categorized in this publication as disposal programme management, stakeholder involvement, disposal system development and implementation. The cost of constructing, operating and decommissioning the facility is estimated at US $56 billion, and the cost of waste transport at US $20 billion.

Note: The cost of implementing large geological disposal programmes, such as the ones in France, Germany, the United Kingdom and the United States of America, runs into the tens of billions of US dollars. The cost of implementing small to medium sized programmes is usually in the order of billions of US dollars.

The extent of the disposal project, in terms of waste quantity, is not always the main cost driver. For instance, for the construction of the encapsulation plant, it is more likely that the installed production capacity, in terms of waste quantity per year, is the main cost driver. For the construction cost of the underground repository, however, a largely proportional relation to the total waste quantity may indeed be assumed.

The same guidance or advice as used for assessing the cost of a WMO can be used for assessing the cost of the on-site organization. These costs will mainly be labour costs, including overheads. The labour costs can be more significant than for the WMO, because more staff work on a nuclear site. It is necessary to draw up an organization chart and estimate the labour rate of each function. Similar to the WMO, the workforce and tasks of the on-site organization might vary over the lifetime of project implementation; and where the workforce decreases, severance pays might need to be provided for.

Other programmes can serve as examples of what might be part of the tasks of such an organization. Apart from the costs of designing, constructing and outfitting, operating, maintaining or upgrading and closing these facilities, the costs of utilities, such as electricity, water and heating, and taxes and insurance need also be included.

6. RISKS AND UNCERTAINTIES

The previous sections described how the overnight cost of the disposal programme can be estimated. This estimate is only a forecast and is therefore inherently uncertain. Disposal programmes are often complex, facing many scientific, technical, societal and political challenges and with many stakeholders involved. Their development and implementation may stretch over very long time spans, during which the nature of the challenges faced will undoubtedly change. It is therefore unlikely that the disposal programme will evolve exactly as envisaged at the outset.

As explained previously, estimating the overnight cost of the disposal programme requires defining a disposal programme. It is often not possible to completely define the disposal programme, and certain assumptions will need to be made to bridge the gaps in its scope. These assumptions may, for example, include the waste inventory to be disposed of or the geology of the selected disposal site. The programme will therefore carry a number of inherent risks and uncertainties.

Because of their complexity, the involvement of many stakeholders and the length of the time spans for their development and implementation, the uncertainties for disposal programmes are generally larger, with potentially greater cost risks, than those associated with more conventional industrial projects. This is exacerbated by the limited experience that exists in implementing disposal programmes and the lack of real cost examples.

Another particular aspect of a disposal programme is the potentially long time that may elapse between the period during which the funding for the project is committed and when the actual expenses arise. Cost estimates for the disposal programme are needed well before it is implemented, in order to know how much funding is needed and to determine the tariffs that waste producers need to pay. The disposal options, the disposal site and the waste inventory for disposal are, however, not always known at the time of the cost estimate.

These uncertainties and risks should be reflected in the cost estimate. Dealing with uncertainties and risks is no easy task. Nevertheless, it is a crucial aspect of a cost estimate and should therefore receive sufficient attention. An approach to dealing with uncertainties and risks usually consists of the following elements, which are further discussed in Sections 6.1–6.4:

(a) Identification of the uncertainties and programme risks;
(b) Sensitivity analyses for various scenarios to develop a range of possible cost outcomes;
(c) Developing a risk management framework to mitigate the potential impact of the risks;
(d) Ensuring provisions are set aside to cover the cost impact of the uncertainties and risks.

When addressing risks and uncertainties, it is important to make a distinction between uncertainties that remain within the scope and definition of the disposal programme, and those that change the disposal programme's definition. The first are referred to as in-scope uncertainties, while the latter are referred to as out-of-scope uncertainties.

Examples of in-scope uncertainties include delays or work interruptions due to weather, equipment breakdown and material delivery problems, among other things. Such events can be expected, but it cannot be known in advance how frequently they will happen and what their impact will be. Examples of uncertainties that may affect the scope or definition of the programme are the selected disposal option or site, the disposal depth in the case of geological disposal or the waste inventory. These out-of-scope uncertainties in this publication are designated as risk events, and treated as such. They relate to situations which, though not expected to occur, could result in cost increases.

Leo and Warhoe [77] recommend that the cost estimate be either prepared or reviewed by a third party. This can avoid optimism bias and an underestimation of the impact of the uncertainties and risks.

6.1. IDENTIFICATION OF RISKS AND UNCERTAINTIES

Assessing risks and uncertainties in the cost estimate requires mapping and registering them. This does not necessarily mean that the identified risks and uncertainties need to be incorporated in the estimate. It may be appropriate to decide not to take account of certain risks, as it might be very difficult or not meaningful to consider them in the cost estimate. Nevertheless, it is important when identifying risks and uncertainties to try to be as complete as possible, and only in a second step, when considering how the identified risks and uncertainties can be dealt with, to exclude some. It will also be important to justify why certain risks are excluded.

The register of uncertainties and risks can be structured according to the WBS presented in this publication. This section will also be structured according to the disposal programme's components as identified in the WBS of Section 4.

As explained in Section 3, the baseline description of the disposal programme should document all assumptions. The list of assumptions will help to identify the risks and to build an uncertainty and risk register. An uncertainty and risk register will also help in identifying and prioritizing potential studies to reduce the cost risks and uncertainties. In addition, it will be important to regularly review and update the register. Sections 6.1.1–6.1.4 describe the potential uncertainties and risks relating to the high level components.

One of the most significant uncertainties concerns the schedule or planning for the disposal programme, and it is important to identify uncertainties on the planning and the risk of delays. Delays can result from a longer licensing process, stakeholder opposition or a need for more RD&D than was originally anticipated. Examples of programme delays are included in the tables presented below.

A delay in the disposal programme can affect costs in several ways. A delay can lead to a decrease in the expected costs due to technological improvements or to increased experience and expertise in implementing the disposal project. The delay may, on the other hand, also lead to higher costs for interim storage, or more stringent regulations may have come into force by the time the programme is implemented.

One of the most important impacts of planning on the cost has to do with the discounting practices used to determine the amount of funding that is needed to implement the programme. The required amount of funding depends on the planning, the expected cost escalation and the financial return on funds (see Section 7).

6.1.1. Disposal programme management

The management of the disposal programme relates to the activities within the control of the WMO. Uncertainties on the cost of managing the disposal programme mainly concern the required human resources (i.e. the workforce needed and their salaries).

Disposal programme management involves the risk that a lack of human or financial resources could slow down or stop the programme. Lacking the appropriate expertise and financial resources can jeopardize the good and efficient execution of the disposal programme and in turn lead to higher costs than initially foreseen. This means that a cost assessment which underestimates the cost of disposal can itself constitute a risk for the disposal programme.

6.1.2. Stakeholder involvement

The goal of stakeholder involvement is to develop a widely acceptable and broadly supported disposal solution. As described in Section 5.2.2, stakeholder involvement entails a wide range of activities, such as organizing workshops, performing sociopolitical research, publishing newsletters, organizing site visits, social media management and operating an information centre. Uncertainties on costs mainly relate to what will be done or what is needed to involve stakeholders. The number of stakeholders with whom the programme needs to be involved can be uncertain and is sometimes underestimated.

The direct costs and in-scope uncertainties relating to those activities are generally small compared to disposal system development and implementation. Investing in stakeholder involvement may, however, reduce the risk of developing a disposal solution that is not accepted by several stakeholders, and may therefore save time and resources.

There are several examples of disposal programmes that have failed to gain the necessary stakeholder support. This, for example, happened to the Nirex scheme for the development of a rock characterization facility as part of the United Kingdom's programme for the geological disposal of LLW and ILW in 1997 [78], and to the Yucca Mountain project in the United States of America in 2010. At that stage, US $14 billion had already been invested in the latter project [79].

In 1977, a salt dome was selected at Gorleben (Germany) for the disposal of radioactive waste, especially heat producing radioactive waste and spent fuel. Exploration of the salt dome was discontinued in 2012 following a political consensus to set up a new siting process [64].

In many cases, where a programme has been stopped, governments have reviewed the site selection process and the reasons for the failure to find a site. This usually leads to a new process being initiated. Examples of this include site selection programmes in Belgium, Canada, France, Germany and the United Kingdom.

Finally, the licensing process is usually a first-of-a-kind project for the regulator. Sufficient time should be foreseen for the regulator to evaluate the licence application. Different regulatory processes will need to be aligned, which may take time.

6.1.3. Disposal system development

Disposal system development mainly concerns site characterization, safety assessments, facility design and licensing process applications, and the RD&D efforts supporting those activities. This can include the construction of a URL and the execution of large scale experiments.

The cost uncertainties concern the amount of effort that is needed to achieve the specified goals (i.e. sufficiently characterizing the site, demonstrating the safety of the disposal facility, developing a design for the disposal facility). The programme might need to contain some innovative elements which require further testing and research before being used or deployed in the programme.

Disposal system development contains risks that can change the programme's scope, as the outcome of the development work can be uncertain. A programme can embark on developing a disposal solution at a specific site, but site characterization or the site specific safety assessment could demonstrate that the site is not suitable. Innovative technologies might be envisaged, but it might become clear during the development of those technologies that they have significant shortcomings. Such unfavourable outcomes can result in an extension of the research programme, leading to an increase in its cost, or even to a redirection of the overall disposal programme (see Table 9).

TABLE 9. EXAMPLES OF EVENTS THAT HAVE AFFECTED DISPOSAL SYSTEM DEVELOPMENT

	Event
Belgium [80, 81]	Before adopting its current supercontainer concept, ONDRAF/NIRAS envisaged disposing of its HLW in canisters that were to be placed in a stainless steel disposal tube axially centred in the disposal gallery.

TABLE 9. EXAMPLES OF EVENTS THAT HAVE AFFECTED DISPOSAL SYSTEM DEVELOPMENT (cont.)

	Event
Belgium [80, 81]	The annular space between the tube and the concrete gallery lining was to be filled with a bentonite based buffer material. A mock-up of this system was built and tested. However, the experiment revealed the complex behaviour of the engineered barrier and the existence of several processes potentially detrimental to the corrosion resistance of metallic components. Based on this outcome, and the feedback from an international peer review on the engineered barrier system, the system was abandoned.
United States of America [82]	A conceptual design of the Project Salt Vault in an existing salt mine at Lyons, Kansas, was completed in 1971. However, two basic technical problems with the siting were raised that same year. A large number of existing oil and gas boreholes that were detected in the vicinity of the potential repository raised concerns as to what extent groundwater flow through these boreholes could lead to the dissolution of the surrounding salt and eventual breaching of the repository. Another concern was raised when during solution mining, about 5 km from the proposed repository, large volumes of water were unaccountably ‘lost’, presumably because they flowed into pre-existing openings or hydraulic fractures. Because of these technical concerns and because of public and political opposition, the project was abandoned. Potential salt repository sites were also being considered in Alpena, Michigan, and Carlsbad, New Mexico. The Alpena site was abandoned due to local opposition, but the local politicians of Carlsbad saw this as an opportunity to put forward their location for what was to become the WIPP for defence transuranic waste.

6.1.4. Disposal implementation

The uncertainties surrounding the design of disposal facilities create a cost uncertainty. Those design uncertainties do not necessarily imply that there is a risk of an increase in the cost. They might constitute opportunities for reducing the cost as well.

Uncertainties can concern the unit costs of the activities, materials or equipment that are required during the project, and the duration of activities or required quantities of materials or equipment. One example is the waste disposal rate. Before waste disposal is actually carried out, the rate at which it will be performed is a design parameter with associated uncertainty. If the disposal rate is overestimated, the estimated duration of the disposal campaign and the related cost will be underestimated. This highlights the importance of properly allowing for downtime. Equipment repair or maintenance and work interruptions due to weather or accidents need to be considered when evaluating the expected number of hours for which the facility will operate per year.

There is, however, one important difference between disposal projects and more conventional industrial projects, and that is that they usually have longer timescales for implementation. These longer timescales lead to larger uncertainties for the disposal projects and make them more vulnerable to risks. For instance, longer timescales increase the chance that the regulations or international best practices will evolve, requiring the design of the facility or the way it is operated to be changed (see Table 10).

TABLE 10. EXAMPLES OF EVENTS THAT HAVE AFFECTED DISPOSAL IMPLEMENTATION

	Event
Finland [83]	Nuclear waste producers are obliged to present a cost estimate for the management of their existing waste every three years, including spent fuel disposal and decommissioning of facilities. The estimate in the period 2010–2013 increased by about 12% compared to the previous period. The increase was mainly due to an increase in the general price level and modifications of the decommissioning and disposal plans.

TABLE 10. EXAMPLES OF EVENTS THAT HAVE AFFECTED DISPOSAL IMPLEMENTATION (cont.)

	Event
France [84]	The evolution of safety rules and requirements led to evolution in the concept used between the former monoliths and tumuli of the Centre de la Manche facility (designed before 1969) and the sturdy concrete vaults at the Centre de l'Aube repository (designed before 1992). The Bure URL had a fatal accident in 2002 during a preliminary phase of shaft construction, which delayed construction for a year.
Germany [84]	As in France, a fatal accident in the Gorleben URL in 1987 led to a pause for 20 months.
Switzerland [36]	The 2016 cost estimate for waste management showed an increase of 5% compared to the 2011 estimate. This difference was partly due to changes in the cost estimation method (costs are no longer a 'best estimate' but also include costs for uncertainties, hazards and opportunities and variants) and changes in projects.
United States of America [85–88]	In February 2014, two accidents happened at the WIPP facility: a truck caught fire; and nine days later, an air monitor measured airborne radioactivity close to the location where waste was being emplaced. These accidents led to a stop in facility operation. Limited operations resumed in January 2017. Full operations cannot, however, resume until a new ventilation system has been completed. The USDOE estimate the recovery costs at US $242 million, a portion of which will be drawn from the base budget for WIPP operations. The major cost drivers include facility programme and safety documentation enhancements and revisions, mine habitability and operations, facility upgrades, waste emplacement operations, operational readiness assessments and programme management support. In addition, a new permanent ventilation system, estimated at US $65–261 million, and a supporting exhaust shaft, estimated at US $12–48 million, need to be constructed. This could bring the direct remediation costs up to US $550 million. In addition, a settlement of US $76 million was paid to the state of New Mexico. Finally, there is the loss of a facility that is not operational and the costs for extended storage of the waste. The annual budget for operating the WIPP disposal facility in the years before the accident was around US $134 million. This gives an indication of the costs for each year that waste operations are suspended.

Changes in the legal and regulatory framework may increase the disposal cost as additional requirements on disposal facilities, such as building in requirements for monitoring and retrievability, might be imposed. New requirements may affect programme development or implementation and may take the form of the rework or even modification of existing facilities, leading to programme delay. Health and safety issues or regulations tend to become more stringent over time as well and will require further investment. The same can apply to security costs. The costs of implementing such requirements can be very significant, and in extreme cases can change the scope of the disposal programme.

Accidents form another risk, as they can delay the programme and lead to costs for remediating the site or facility. Some accidents can even have an impact on the whole industry, as demonstrated by the WIPP accident (see Table 10).

Finally, there is the risk of a lack of funding to implement the programme until completion. This is addressed in Section 6.2.

6.2. SENSITIVITY AND SCENARIO ANALYSIS

As a best practice, a cost estimate should include a sensitivity analysis, which examines how the variation of a single assumption or parameter affects the cost estimate while holding all other parameters constant. By doing so, the cost drivers which have the largest impact on the cost estimate can be determined.

When changing the parameter values, it is important to make sensible changes. It is not useful to change parameters to a degree for which there is no valid basis. The degree to which parameters are changed should be well considered and preferably provided with justification.

The outcome of the sensitivity analysis will provide an insight into which parameters or assumptions have a strong impact on the estimated cost. Based on this information, it can be decided to make the cost estimate more robust or better substantiated by further evaluating and justifying what is the best possible value for cost sensitive parameters. The analysis can also result in a better understanding of the reasons why the estimate varies depending on some parameters. This can help in identifying possible cost risks and developing a plan to manage those risks (see Section 6.3).

A sensitivity analysis generally examines the effect of changing one parameter at a time. It is however important to also evaluate the impact of changing multiple parameters in relation to a specific scenario. Such a scenario can, for example, be a change in the type of host rock, which will probably affect a series of parameters. Developing different scenarios can be particularly useful for programmes that are at an early stage and for which no specific programme can be defined. In some cases, the changes can be so significant that it is more beneficial to develop multiple baselines. This could, for example, be the case when the disposal concept is radically changed, say from surface to geological disposal.

Sensitivity and scenario analyses will result in a range of potential costs instead of a single point estimate and provide possible reasons for the effect some parameters have on the cost (see Table 11). They therefore provide a better picture of the possible cost, the related uncertainty and the possible risks.

TABLE 11. EXAMPLES OF THE DIFFERENT SCENARIOS

	Scenario
Belgium [62]	The Belgian Government decided in 1993 to suspend the reprocessing of spent fuel from nuclear power plants. ONDRAF/NIRAS is, however, required to give equal consideration to the study of the long term management of reprocessing waste and that of non-reprocessed spent fuel. It therefore estimates the cost of two scenarios: one reference scenario in which there will be no spent reprocessing in future; and an alternative scenario where all spent fuel will be reprocessed.
Czech Republic [89]	SÚRAO considers two scenarios in its cost estimate for a GDF: one in which the facility is operated following a two shifts per day system and one in which there will be three shifts per day during the facility operation.
Japan	Japan worked with 11 scenarios for soft rock and one for hard rock. This resulted in a range of possible cost outcomes, so although the type of host rock and other parameters were not known, by estimating the costs of a range of possible scenarios, a good first idea of the cost range could be obtained. From those 11 scenarios, it selected the most probable one as the reference scenario.
Slovenia [68]	The cost estimate of the LLW and ILW repository considers a scenario in which the repository is developed and implemented by Slovenia alone, and one where it is developed and implemented together with Croatia.
United Kingdom [76]	The RWM geological disposal programme for higher activity radioactive waste is at an early stage. Consequently, there are many uncertainties and could, for example, concern the disposal site or concept to be selected. RWM has therefore identified geological settings that are potentially suitable to host a GDF and has subsequently developed a range of geological disposal concepts that are potentially appropriate for the disposal of the different types of radioactive waste and has identified host rock formations. Subsequently, one reference case was selected as a basis for planning assumptions and for a cost estimate. Apart from calculating the cost of the reference case, a parametric cost model was developed which considered six major variables: project schedule, repository location, repository depth, engineering layout, volumes of waste and types of waste. This resulted in a better understanding of the impact that variances in one of the parameters could have on the overall cost.
United States of America [90]	A set of 16 geological disposal concepts are defined to come to a cost estimate for the geological disposal of spent fuel. The disposal concepts consider three different types of host rocks (crystalline, salt and argillaceous) and four waste package sizes.

6.3. RISK MANAGEMENT

Risk management is the process of identifying risks, evaluating their possible impact on the disposal programme and its cost and developing ways to minimize the probability or impact of the risk. Risk management should also include the identification of possible opportunities which can lead to a reduction of the cost.

Risk management may require investing in human and financial resources. Those investments can, however, save much larger costs in the future. The example of the WIPP accident (see Section 6.1.4) demonstrates the high costs that can result from an accident. The cost of investing in accident prevention (e.g. by training staff, working with proper equipment) will usually be a fraction of the costs relating to accident recovery.

Risk management is mainly useful to address those events that can change the programme's scope (e.g. the loss of stakeholder support, significant changes in the disposal concept or design such as a change of site or disposal option, changes in regulations). An organization can decide to set aside provisions to cover some of the related cost risks (see Section 6.4.2), but even then, developing a risk management plan to mitigate the identified risk is a best practice. Risk management should therefore be part of disposal programme management and the cost of risk mitigating measures should be included in the overall cost estimate (see Table 12).

TABLE 12. EXAMPLE OF RISK MANAGEMENT

	Risk management
Belgium [91]	In 2009, ONDRAF/NIRAS organized a public consultation on geological disposal. There was demand from the participants in that consultation to keep the possibility open to retrieve the waste after repository closure. ONDRAF/NIRAS took account of this demand in its development of the GDF. The demand, for example, plays a role in the design of the repository backfill material and seals. The design of these components needs to ensure that the backfill material and seals can be removed again, enabling waste retrieval. Furthermore, it is one of ONDRAF/NIRAS strategic choices guiding the development of a GDF to prefer the use of materials and implementation procedures for which broad experience and knowledge already exist.

Risk management is a continuous process as the risks change when the programme evolves. Some risks might recede while the likelihood and consequences of others may change as the programme matures. More information on risk management can be found in the Green Book [30], and in the guide published by the USGAO [33]. The Green Book [30] describes some risk mitigating approaches:

(a) Design flexibility: It may be worth developing a flexible disposal design that can accommodate for changing (scientific, technological, regulatory, societal) conditions.
(b) Insurance: The WMO might decide to insure against certain risks.
(c) Best available technology (BAT): Applying the principle of BAT in the development of the disposal solution will lead to preferences for materials and procedures for which broad experience and knowledge already exists and for technologies with proven effectiveness.

6.4. PROVISIONS

It is unrealistic to assume that a disposal programme will not encounter any delays, problems or unforeseen events which will lead to additional costs. It is therefore necessary to put aside provisions to cover those costs. It is important to distinguish between provisions for in-scope uncertainties and provisions for risks affecting the scope of the disposal programme.

Provisions for in-scope uncertainties are called contingencies, which need to cover expenses relating to problems that do not alter the programme's scope (e.g. weather, logistical delays, equipment breakdown). These are events that are likely to occur, but the frequency or impact of which cannot be predicted in advance.

Provisions can be set aside as well for out-of-scope uncertainties or risks, such as changes in regulation or nuclear policy, the loss of stakeholder support or a change of disposal concept or disposal site.

The crucial difference between contingencies and provisions for funded risks is that the former are expected to be fully incurred during the development and implementation of the disposal programme, while the latter may or may not be spent. Consequently, contingencies should form an integral part of the estimate. Whether or not provisions are set aside for certain risks is the organization's decision.

Contingencies for in-scope uncertainties and provisions for funded risks are shown in Fig. 7, which shows these different elements of a cost estimate. The figure also shows that allowances and the costs of risk mitigation make part of the overnight cost estimate. As discussed in Section 6.3, risk management should be part of the disposal programme management and the cost of risk mitigating measures should be included in the overall cost estimate.

Allowances and contingencies should not be confused. As described in Section 5, allowances are added to the cost of an item to take account of the costs that will occur, but which cannot be precisely determined because of a lack of detailed knowledge (e.g. costs for furnishing, telecommunications, utilities). Determining the contingency to take account of in-scope uncertainties is further discussed in Section 6.4.1, while provisions for funded risks are addressed in Section 6.4.2.

Figure 8 shows how the cost estimate may evolve over time as the disposal programme goes from the early planning phase towards more detailed planning close to the implementation phase and a programme that is being implemented.

As the programme matures, the scope becomes better specified and more complete. This will increase the estimated cost. In addition, some uncertainties and risks will have 'materialized'. Other uncertainties and risks will have receded and will need to be removed from the contingency or the provisions, reducing the overall uncertainties and risks. Figure 8 shows an ideal scenario where the estimate, including provisions for in-scope and out-of-scope uncertainties, remains more or less constant. In reality, this is often not the case, as many projects are confronted with cost overruns [93]. This again underlines the importance of addressing cost uncertainties and risks and setting aside provisions. The figure also shows that a cost increase would have happened if insufficient contingencies and provisions were foreseen.

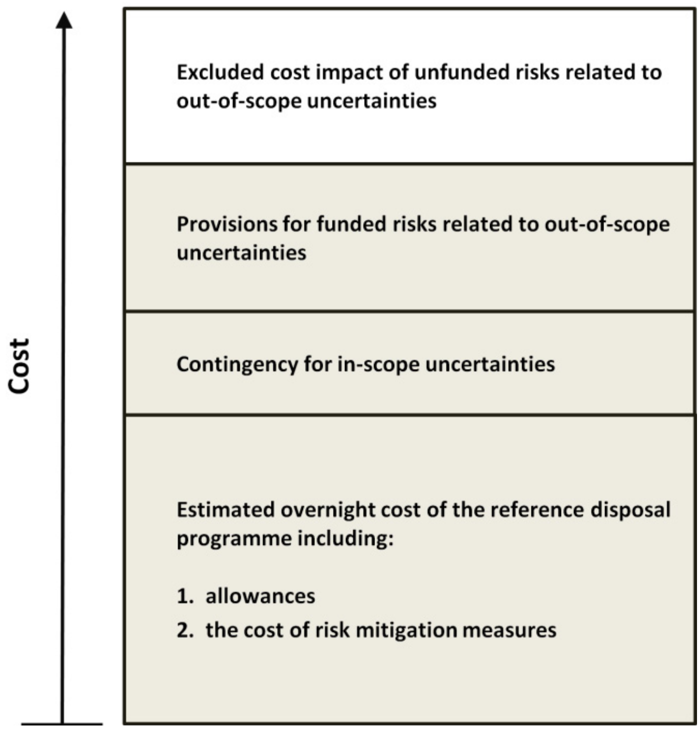

FIG. 7. Elements of the cost estimate [92]. Note: Shading indicates the elements that are included in the estimate.

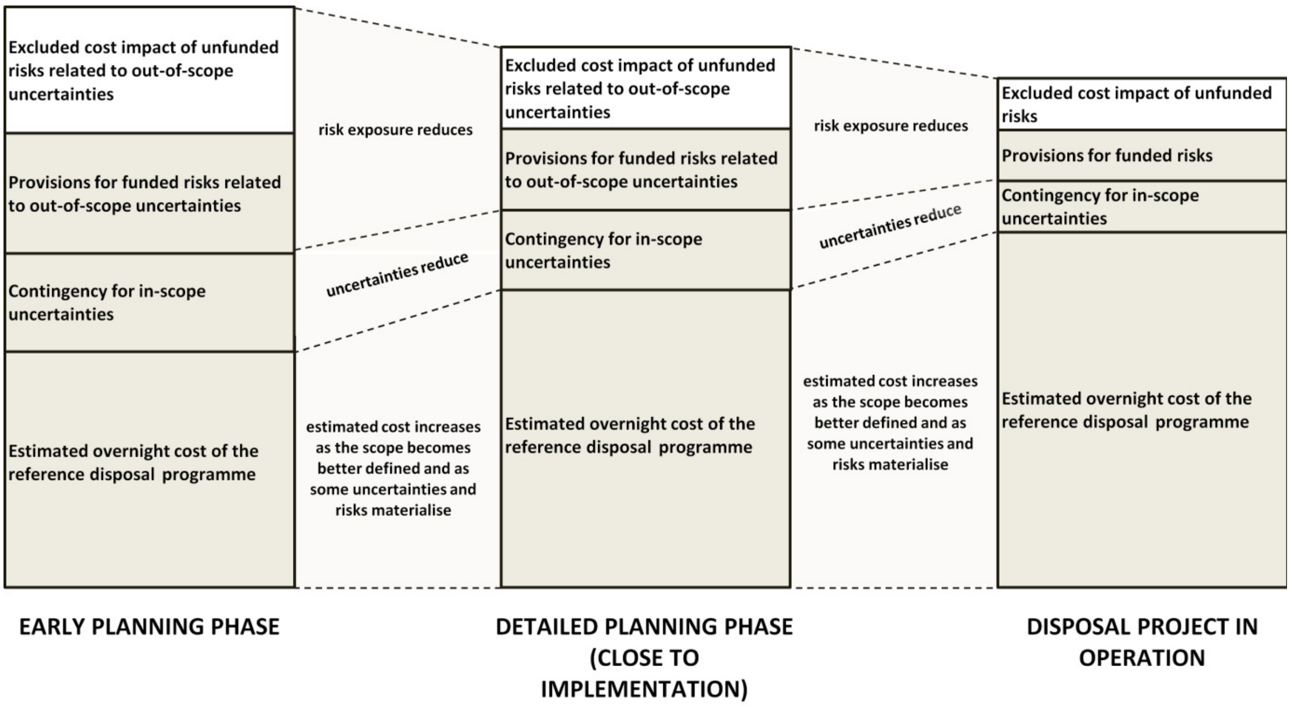

FIG. 8. Evolution of the cost estimate elements as the disposal programme progresses [92].

6.4.1. Contingencies for in-scope uncertainties

The cost assessment can take account of uncertainties by adding contingencies. A contingency is an amount added to an estimate to allow for additional costs that experience shows will likely be incurred. They are usually expressed as percentages of the estimated cost and are added to the estimated cost: cost (including contingency) = cost (without contingency) × (100% + contingency).

The contingency reflects the degree of uncertainty on the estimated cost of a cost element or of the disposal programme as a whole. At the beginning a programme might still be very conceptual and it might have a high degree of uncertainty caused by the lack of a specific project definition. The contingency for such a programme will be high. As the programme becomes more precisely defined, the number and degree of unknowns decreases. This will be reflected in a smaller contingency.

An equivalent approach should be followed when planning the disposal programme. The time to perform the different tasks and activities in the programme should be estimated and certain margins should be foreseen. These margins should be based on empirical evidence.

A range of methodologies to quantify the contingencies exist. They can be derived from cost contingency practices and standards or from a cumulative probability distribution derived from a statistical method. This second method provides more information and results in a more detailed picture of the cost impact of the different uncertainties. However, it is usually more time consuming and complicated, as alternative scenarios have to be developed and their probability needs to be evaluated. Examples of cost contingencies in different disposal programmes are given in Table 13. The different methods of determining the contingency are described in Sections 6.4.1.1 and 6.4.1.2.

Determining the contingency is not a one time activity. When the programme evolves, the uncertainties change, and these changes need to be reflected in the contingencies as well. Some uncertainties might not have materialized and the related contingencies should in such a case be removed [96]. It is therefore important to regularly interrogate the cost estimate and the contingencies and update them.

Contingencies should also not be seen as an item for potential cost saving. The contingency is an integral part of the estimate as it is the way to incorporate the cost of events that are expected to occur. They are not only important to give a realistic estimate but also to avoid loss of stakeholder confidence due to programme delays or overspending. Stakeholders expect programmes and projects to be ahead of schedule and under budget.

TABLE 13. EXAMPLES OF COST CONTINGENCIES

	Cost contingencies
Australia [72, 73]	The cost estimate for the spent fuel and ILW repository in South Australia includes a contingency of 25% to account for optimism bias. The figure chosen reflects the measured difference in costs between the time of the original announcement and the point of final project delivery for Australian public–private partnership projects. Furthermore, a sensitivity analysis showed that the base estimate represented a probability level of P25. Increasing this base estimate with the 25% contingency resulted in an expected life cycle cost of US $97 billion, which is at a P50 probability level. To arrive at a probability level of P90, the base cost needs to be increased by a contingency of 87%.
Belgium	Contingencies are assigned to each cost in the WBS, determined following the EPRI approach (see Section 6.4.1.1).
Hungary	The cost estimate of the Bátaapáti LLW repository does not contain a contingency.
Japan	No contingency is used in the NUMO cost estimate of the HLW GDF.
Slovenia [69]	The cost estimate of the repository for LLW and ILW assumes an average 17.2% contingency if developed and implemented by Slovenia alone, and an average 17.4% contingency if the programme is developed and implemented together with Croatia. The ratio of these contingencies over the total project costs are 4.8% and 5.5%, respectively.
South Africa [70]	As the low level disposal facility in Vaalputs has been in operation since 2006, the life cycle cost of the facility can be reasonably well estimated. Therefore, no contingency is included in the cost estimate for the facility.
Sweden [35]	SKB uses a statistical method to incorporate uncertainties into the determination of the fees. The method is based on a calculation principle called ‘the successive principle’ (see Section 6.4.1.2).
United Kingdom [94]	For the GDF in the United Kingdom, the cost estimate does not include risk or contingency. However, to minimize the risk to the taxpayer, for waste arising from planned new build nuclear power plants, the Government has developed a waste transfer pricing approach that considers certain programme and technical uncertainties.
United States of America [29, 95]	The USDOE considers the contingency method from AACE International as best industry practice and uses it in the cost estimates of its waste management projects. Similar to the EPRI method explained in Section 6.4.1.1, the AACE International methodology considers both project and process contingencies. The project contingency is based on the degree of uncertainty of the project and compensates for inaccuracies associated with the project stage. The process contingency is based on the degree of uncertainty in the technology used. The 2001 analysis of the Yucca Mountain life cycle cost applied a contingency of 19% on estimated future costs.

Note: Belgium and the United States of America apply Electric Power Research Institute (EPRI) and AACE International methods to determine the contingency on each item in their WBS. Canada, Lithuania and Sweden apply a probabilistic approach to determine the level of the overall contingency. Some States, such as Hungary, Japan and South Africa, do not include contingencies in their cost estimates.

6.4.1.1. Contingency practices and standards

Examples of cost contingency practices and standards for construction projects include those by AACE International, the American National Standards Institute and the EPRI. Most of these methods make a distinction between project and technology contingencies. Project contingencies reflect uncertainties relating to the maturity of the project. This type of contingency covers expected omissions and unforeseen costs caused by an incomplete definition of the project and its engineering. Project contingencies thus compensate for the inherent estimate inaccuracy associated with each stage of the project.

Technology contingencies reflect uncertainties related to the maturity of the technologies used. They are based on the degree of uncertainty caused by the use of innovative technologies. It is an effort to quantify the uncertainty in performance because of limited technical data. The EPRI method uses four levels of project contingencies and five levels of technology contingencies (see Table 14).

TABLE 14. CONTINGENCIES USED IN THE EPRI METHOD

Project contingencies		Technology contingencies	
Simplified planning (conceptual screening)	30–50%	New concept for which little or no comparison exists	≥40%
Preliminary planning (feasibility study)	15–30%	New design for which a preliminary design analysis has been performed	30–70%
Detailed planning (budgeting stage)	10–20%	New design for which a more advanced design analysis has been performed, possibly involving prototype testing	20–35%
Final or near final planning (tendering stage)	5–10%	Modified design derived from an existing design already commonly used in the industry	5–20%
		Design commonly used in the industry	≤10%

Project and technology contingencies are assigned to each element in the WBS. The values of the contingencies need to be decided by the cost estimator. This is preferably done in collaboration with the managers, engineers and scientists working on the disposal programme. Providing each value with a short justification can make it easier when the cost estimation and the contingencies are updated at a later stage.

As this method assigns contingencies to the different WBS elements, it is suitable for uncertainties that are within the scope of the disposal programme, but less so for uncertainties that affect the scope or definition of the disposal programme, as these uncertainties are likely to change the programme breakdown itself. For example, in the case of a geological disposal programme, the cost of constructing waste disposal tunnels might be uncertain because the frequency of work interruptions is not known in advance. A percentage of the estimated cost can be added as a contingency where the value of the percentage can be based on experience from the past in similar projects. The tunnel construction cost will, however, also be uncertain if no decision has been made about the host rock formation in which the disposal facility will be constructed. Different host rocks might affect the tunnel sizes, lengths, excavation technique used and the necessity for or type of tunnel supports. It becomes difficult to capture these uncertainties in a percentage using the method described here. For those uncertainties that affect the programme's scope and definition, it is more useful to develop several scenarios and apply a probabilistic approach.

6.4.1.2. Probabilistic approach

An overall cost contingency can also be derived from a cumulative probability distribution of the cost. Such a distribution plots the estimated cost against the probability that the actual cost will be lower than or equal to that cost (see Fig. 9). The P50 and P80 lines indicate the costs for which there is respectively a probability of 50% and 80% that the actual cost will be lower than or equal to this cost.

SKB uses such a statistical method to consider the variations and uncertainties that naturally appear when assessing the costs of a project. The method is based on a calculation principle called the successive principle, which was developed by Lichtenberg [97].

Each cost item and each uncertainty are described as stochastic variables to which probability distributions are assigned. The functions are chosen so that the probability distribution matches the character of the variation as closely as possible. Special properties of the variation, such as a pronounced imbalance of the outcome or an 'either/or value' (discrete distribution), will have an impact on the choice of probability function.

Monte Carlo simulations are then used to randomly combine the impacts of the various uncertainties. This is done by performing the calculation a number of times. In each calculation, all cost elements are given a value based on the selected probability distribution. Monte Carlo analysis also allows taking account of the correlations that exist between different items. Each calculation thus simulates the implementation of the programme. By doing this

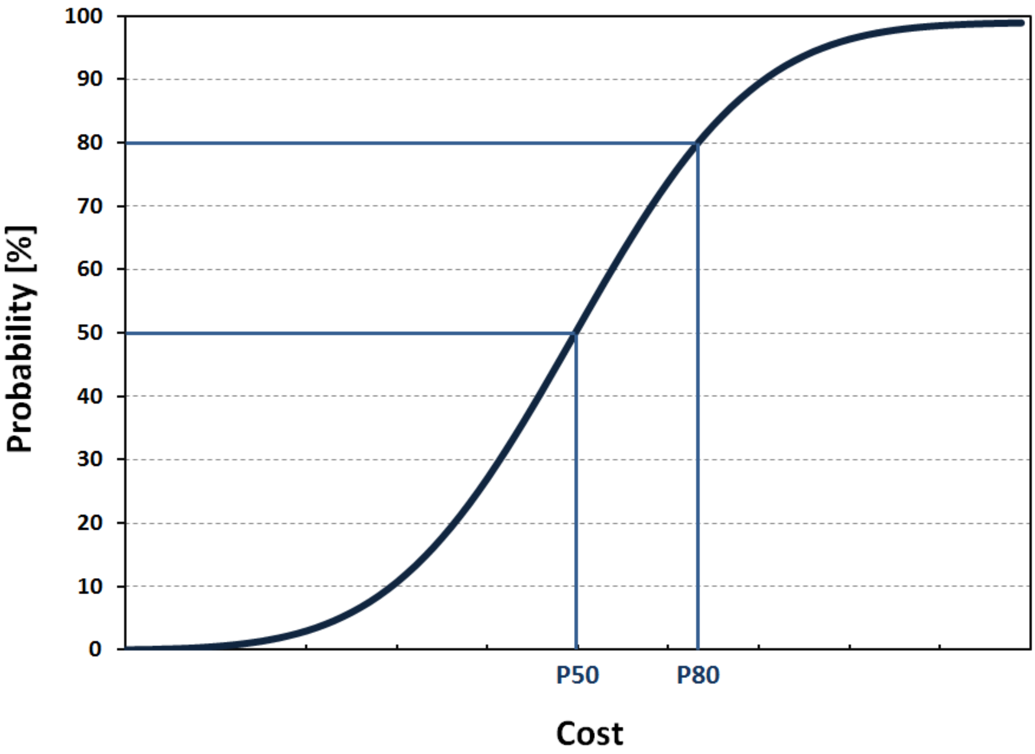

FIG. 9. Cumulative probability distribution of the cost.

a great number of times, a range of outcomes for the costs is generated, which can be plotted against their number of occurrence. This results in a probability distribution of the overall cost of the disposal programme (see Table 15).

TABLE 15. THE SUCCESSIVE PRINCIPLE AND THE PROBABILISTIC APPROACH APPLIED IN SKB PROBABILISTIC COST ESTIMATES

	Comment
Approach	Based on the successive principle developed by Lichtenberg [97], SKB uses a probabilistic approach to deal with the uncertainties relating to its geological disposal programme. SKB first calculates the cost of a reference scenario, which reflects the nuclear power companies' current plan of operating the newest reactors for 60 years. The cost calculation of the reference scenario is done in a traditional manner: the programme is broken down into more specific items and the probable costs of each item are estimated and added to arrive at the total cost. The regulation, however, stipulates that an operating time of 40 years needs to be considered for the fee calculation (see Section 7.2.2). Therefore, the cost of this scenario is calculated in a next step. This results in a best estimate of US $8 billion, without taking account of any uncertainties [35]. It is in the next step that the probabilistic approach is applied to incorporate the cost impact of the uncertainties. This approach consists of the following five steps.
Step 1. Identify and group uncertainties	An analysis group is established with a broad based membership from areas linked to nuclear activities, as well as from areas that are detached from such activities. The group brainstorms on the uncertainties of the programme. The uncertainties considered by the analysis group are limited by 'fixed preconditions' determined by SKB, which may entail relatively obvious limitations, such as any necessary steps need to be taken within Sweden's borders. Preconditions can also constitute important policy related aspects, for example that only KBS-3 should be regarded as a method for the final management and disposal of spent fuel. The uncertainties may be of a type that only affects individual calculation objects, such as uncertainty in workforce or canister cost, or they can affect different items in the cost breakdown.

TABLE 15. THE SUCCESSIVE PRINCIPLE AND THE PROBABILISTIC APPROACH APPLIED IN SKB PROBABILISTIC COST ESTIMATES (cont.)

	Comment
Step 1. Identify and group uncertainties	Examples of the latter type include a change in time schedule or changes in regulatory requirements. The identified uncertainties are then grouped into independent categories, which SKB arranges under six categories: (a) Society: Uncertainties on legislation and regulatory matters or political issues in general. (b) Economics: Uncertainties on economic conditions such as the price for labour or materials. (c) Implementation: Uncertainties on the time schedule strategies, siting questions, etc. (d) Organization: Uncertainties on the project management. (e) Technology: Uncertainties on purely technical matters. (f) Calculation: Uncertainties and risks of incorrect assessments (overestimation or underestimation) in the calculation work.
Step 2. Assign values to the uncertainties	Subsequently, a three point estimate is made for each identified uncertainty, which means that low, reference and high values are determined and a probability function is chosen for the uncertainty. The functions are chosen so that the probability distribution matches the character of the variation as closely as possible. Special properties of the variation, such as a pronounced imbalance of the outcome or an 'either/or value' (discrete distribution), will have an impact on the choice of probability function. In that way, the uncertainty is described as stochastic variables with associated distribution functions. Any dependencies between the uncertainties are identified and quantified by a correlation coefficient.
Step 3. Numerical calculations	The probability distributions defined for each identified uncertainty are then combined to produce the probability distribution of the total cost. This is done using Monte Carlo simulations. The simulation by SKB covers 2000 cycles, which is judged to give a sufficient level of accuracy in the results. The mean value of those 2000 simulations is taken. This increases the cost estimate from US \$8 billion to US \$11 billion. The supplementary amount is determined as the P90 value minus the mean value of the Monte Carlo simulations. This amount is US \$1.9 billion.
Step 4. Successive detailing	The simulation also enables ranking the uncertainties in terms of their impact on the cost. The five uncertainties with the highest cost impact in the SKB approach are the uncertainties relating to: (1) Regulations on decommissioning nuclear power plants; (2) Regulations on other nuclear activities; (3) The time for licensing the spent fuel repository and the encapsulation plant; (4) The cost estimate of the spent fuel repository; (5) The time schedule for commissioning the spent fuel repository and the encapsulation plant. A consideration is to further break down the most crucial items and to analyse them in greater detail, after which the calculation can be repeated, resulting in less uncertainty. This can be performed until the unavoidable minimum uncertainty has been reached. SKB, however, does not further break down the above mentioned uncertainties.
Step 5. Action plan	An action plan is made to minimize the uncertainties, including measures against major risks.

The disadvantage of probability calculations is, however, that they require that probability distributions are established for the different uncertainties. This can be quite easy for items for which a lot of data and experience exist. For example, the uncertainty of delays due to bad weather when constructing a building. Many data on this type of uncertainty are surely available in the industry, and establishing a probability distribution should not pose major problems. When, on the other hand, the cost of installing a sealing system in an underground repository needs to be assessed, then the estimator might be confronted with a lack of cost data. It will be more difficult to estimate the probability distribution of the cost of such a system.

6.4.2. Provisions for risks

In this publication, risks refer to those uncertainties that affect the disposal programme's scope. They relate to situations which, though not expected to occur, could result in cost increases. An organization might therefore decide to set aside provisions to cover such possible increases in cost. These provisions may or may not be used during the execution of the disposal programme. As such, they differ from contingencies for in-scope uncertainties as those are expected to be fully incurred during the disposal programme. Hence, contingencies should always form an integral part of the estimate, while the provisions for risks depend on the implementing organization's willingness to foresee the need for such provisions.

It can be a justifiable choice not to fund certain risks, since it might not be meaningful: for example a disposal programme can be halted because of insufficient stakeholder support. When this happens, the invested money is completely, or partly, lost. It does not seem reasonable to put aside provisions for such 'showstopper scenarios'. It is furthermore difficult, or even impossible, to make a meaningful statement on the probability and cost impact of risk that the programme is halted after 10, 20 or 50 years. Such scenarios are dealt with by risk mitigation methods rather than by provisioning for them.

Risk provisions are often in the form of guarantees, such as parent company guarantees, surety bonds and letters of credit. For example, as a precaution against insolvency, the owner may be required to cover the part of the assessed liability not covered by the fund with securities (see Table 16).

TABLE 16. EXAMPLES OF PROVISIONS TO FUND RISKS

	Provisions
Belgium [49, 62]	ONDRAF/NIRAS has set up an insolvency fund to cover any contingent costs associated with failed producers. This fund is financed through a 5% charge to waste producers.
Canada [6, 98, 99]	Ontario Power Generation (OPG) has chosen to furnish external funds as the financial guarantee for all its nuclear power plants and their associated waste management facilities. Until the funds for managing OPG waste have reached a fully funded condition, the Ontario Provincial Government, its only shareholder, provides a supplemental guarantee to the regulatory body, the Canadian Nuclear Safety Commission (CNSC), for an amount covering the unfunded portion of the estimated costs. The Provincial Government also guarantees the rate of return on the investments in OPG decommissioning funds. In 2005, the Government of Saskatchewan initiated development of an institutional control framework for the long term management of decommissioned mine and mill sites. To reduce the province's risk when it accepts custodial responsibility for those sites, the Unforeseen Events Fund was established. The fund will pay for unforeseen future events. Examples of unforeseen events include damage resulting from floods, tornadoes and earthquakes.
Finland [8, 100]	As a precaution against early facility shutdown, the part of the assessed liability not covered by money in the fund needs to be covered by securities (credit insurances, liability bank guarantees, real estate mortgages or liability guarantees by a Finnish association, with mortgages on a nuclear power plant not being accepted) furnished by the licence holder, and given to the Ministry of Economic Affairs and Employment, which has to separately accept each. In addition, supplementary securities are required as a precaution against unforeseen events. These can cover up to 10% of the assessed liability.
Germany [101]	In 2017, the operators of the nuclear power plants had to transfer US $21 billion to a fund for the management of the radioactive waste they generate. They can also transfer the liability for interest rate and cost risks to the State, against the payment of a risk premium of an additional US $8 billion.
South Africa	The overnight cost estimate for the GDF for spent fuel and HLW is not discounted to ensure faster fund accumulation (see Section 7). This can be considered as a form of risk premium against possible underfunding of the disposal programme.
Sweden [35]	In addition to paying a fee, power plant operators need to provide two types of guarantee (a total of US $4.9 billion). The 'financing amount' covers the fees that, although decided, have not yet been paid. The other guarantee is the 'supplementary amount' and is for costs due to unforeseen events.

Note: The examples of stakeholder involvement from Belgium and Canada show how early engagement with stakeholders can minimize the cost risks relating to stakeholder involvement. Stakeholders were consulted early in programme development, which made it possible to take account of their expectations in the design. Both States have also planned for a fund or reserve to cover risks.

7. FUNDING THE DISPOSAL PROGRAMME

The previous sections addressed the question of how much a disposal programme will cost. This section deals with how to ensure that enough money is available at the right time to cover the costs — in other words, how the disposal programme can be funded. This section explores:

(1) The sources and mechanisms for funding: who will provide the funding and how it will be levied (see Section 7.1);
(2) The contribution plan: how much needs to be paid and when (see Section 7.2);
(3) The fund management: how the collected money can be properly managed (see Section 7.3).

Ensuring that the disposal programme can be funded through to its completion is essential to guarantee the safe, long term management of spent fuel and radioactive waste. This is recognized in the Joint Convention [2], which states in art. 22(ii) that "Each Contracting Party shall take the appropriate steps to ensure that…adequate financial resources are available to support the safety of facilities for spent fuel and radioactive waste management during their operating lifetime and for decommissioning".

7.1. FUNDING SOURCES AND MECHANISMS

The most common funding sources are the waste producers and the State. These sources and the mechanisms that can be used to generate the funding are further discussed in Sections 7.1.1 and 7.1.2. Often a combination of both sources is applied. Bank loans and advance payments might also be appropriate ways to fund the early stages of the programme or to fund larger capital investments, such as large construction and infrastructure projects. Different funding mechanisms can be applied for different disposal programmes or for different phases of a disposal programme.

Selecting the most suitable funding mechanism depends on many factors, such as the nuclear strategy and policy of the State, the disposal option, the legislative background and the institutional framework. A State with nuclear power plants in operation will likely adopt a different funding mechanism than a State with only institutional waste. This is also reflected in the conclusion of a 1999 study on radioactive waste management funding schemes in ten EU Member States, Canada and the United States of America which finds that there is no ideal scheme and caution should be exercised when transposing a model from one country to another [102]. Furthermore, some States operate a single fund for decommissioning and waste management, while other States have separate funds for each. There may be a single fund for a fleet of reactors or individual funds for each.

The funding mechanism may also depend on the type or category of waste. For the disposal of ILW and HLW, provisions almost always need to be set aside as the period between the generation of the waste and its disposal can be very long. For LLW and spent fuel or HLW disposed of during the operational period of the nuclear plant, it is quite common that the waste producers pay for disposal from their operating revenues. In Sweden, for example, the disposal of short lived operational waste from nuclear power plants is paid directly by the nuclear power plants, as these costs are considered as operating costs, similar to waste treatment [48].

Finally, it should be made clear that the borehole disposal of disused sealed radioactive sources is a particular case. This disposal concept is developed to provide a disposal option for countries with a small radioactive waste inventory and limited resources. The estimated cost of this disposal option is in the order of millions of US dollars. This is very small compared to most surface and geological disposal concepts. For such a relatively small amount, there are more straightforward ways to find funding than the mechanisms described in this section.

7.1.1. Waste producers

It is widely accepted that the organization that creates the radioactive waste is responsible for its safe management (see also art. 21.1 of the Joint Convention [2]), which includes providing the necessary financial resources. This follows the ‘polluter pays’ principle. There are different ways or mechanisms to gather the required funding from the waste producers. The aims of the mechanism should be [102]:

— To ensure long term adequacy;
— To allocate costs fairly;
— To be as straightforward and transparent as possible for all stakeholders;
— To ensure that unit costs are minimized by providing appropriate economic incentives.

For nuclear power plants, a waste management levy based on the amount of electricity generated is one approach. This mechanism is, of course, not applicable to waste producers other than the operators of nuclear power plants.

Another way is to charge the waste producers a ‘once and for all’ charge when the waste is transferred to the WMO, by applying a waste tariff system for different waste categories. A combination of both systems can also be applied. Nuclear electricity producers may fund through a levy, while the waste tariff system is more appropriate for other waste producers [7]. Tariff systems are commonly based on the waste volume. Straightforward and transparent, this system also gives waste producers an incentive to reduce their waste volumes. The disadvantage of this system, which the tariff design needs to overcome, is that other factors, such as activity, toxicity and other complications of disposal, are not taken into account. Waste containing long lived radionuclides or toxic materials might require long term monitoring activities and could therefore justify a higher charge. Nevertheless, such a multicomponent approach becomes more complex and the relative weighting of the different waste attributes is partly subjective, which is why this approach is less commonly used than volume based charges.

Another possible waste tariff system is based on selling space in the disposal facility. Such tariffs can comprise the following:

(a) Proportional costs per unit volume relating to the handling and disposal of the waste, which can be adjusted to take account of other waste characteristics (e.g. content, package shape, activity);
(b) Amortization of prior funding commitments, such as the costs made prior to operating the disposal facility (e.g. infrastructure, stakeholder involvement, disposal system development), which might have been funded by bank loans or prefinancing mechanisms;
(c) Provisions for the closure and post-closure phases of the disposal facility, including activities such as institutional control and post-closure monitoring.

Waste producers can also be charged directly for any disposal services rendered. This is applied for disposal facilities in operation and is therefore more commonly used for the disposal of LLW and ILW rather than for HLW or spent fuel, for which disposal often lies in the future.

Once a certain tariff system has been selected or defined, the specific charges or contributions that need to be paid can be calculated (see Section 7.2). The waste producers’ contributions can be collected in a fund or they can be set aside as provisions on the balance sheets of the waste producers (see Table 17). The manner in which those contributions can be managed is discussed in Section 7.2.2.

TABLE 17. EXAMPLES OF FUNDING THE DISPOSAL PROGRAMME VIA CONTRIBUTIONS FROM THE WASTE PRODUCERS

	Funding
Australia [72, 73]	In 2015, a commission was established by the South Australian Government to investigate the potential for increasing South Australia’s participation in the nuclear fuel cycle. The commission concluded that a disposal facility for spent fuel and ILW that is temporarily stored in storage facilities around the world has the potential to generate substantial profits and significant direct employment. The total cost of the facility was estimated at US $97 billion while the possible revenue was estimated at US $172 billion.

TABLE 17. EXAMPLES OF FUNDING THE DISPOSAL PROGRAMME VIA CONTRIBUTIONS FROM THE WASTE PRODUCERS (cont.)

	Funding
Australia [72, 73]	These figures were obtained by assuming that 138 000 t HM of spent fuel and 390 000 m^3 of ILW would be received and that average prices of US $1.2 million/t HM for spent fuel and US $27 000/$m^3$ for ILW would be charged for the disposal of these wastes. These figures do not represent proposed or recommended prices by the commission, but simply what the commission considered to be a reasonable estimate for the purposes of viability analysis.
Belgium [62]	ONDRAF/NIRAS current waste treatment and conditioning activities are funded by waste tariffs. Its RD&D activities are funded via specific contracts with the waste producers. The long term management activities are funded through the long term fund and the medium term fund. The long term fund needs to cover all costs for storing and disposing of the waste. The medium term fund is to organize a participative process and provide societal support. Contributions to the long term fund are based on the volume of waste and the tariff applicable to the waste category. Contributions to the medium term fund are based on the total capacity of the repository and the respective total quantities of waste from producers intended for disposal. Only waste producers whose total waste quantity exceeds 3% of the repository capacity contribute to the medium term fund. In addition to these funds, there is an insolvency fund intended to finance waste management costs that are not covered following the bankruptcy or insolvency of certain waste producers. The insolvency fund is managed in the same way as the long term fund. It is financed by a reserve of 5% included in the cost of services invoiced to producers by ONDRAF/NIRAS.
Bulgaria	A waste management fund is financed through contributions of the nuclear power revenue: 7.5% of the electricity price goes to the decommissioning fund and 3% to waste management. The cost of handing over institutional waste to SERAW is based on the activity, half-life and/or volume of the waste.
Canada [51]	The cost of the spent fuel geological repository is shared among the nuclear power plants and is based on the number of fuel bundles. The cost sharing does not apply to costs unique to the nuclear fuel waste owner, such as special fuel and transport costs that are owner specific.
Czech Republic [103]	Funding is acquired by a fee of US $4/MW·h for nuclear power plants and a fee of US $2/MW·h for research nuclear installations. Medical and industrial waste producers pay a lump sum (US $11 200 per waste package of LLW or ILW) when handing over the waste to SÚRAO.
France	The management of waste from medical or industrial uses is financed through fees paid by the producers based on a price list. The operators of nuclear power plants set aside US $1.75/MW·h for the waste management and decommissioning costs. Andra's operating costs of the Centre de l'Aube are financed by annual commercial contracts signed with the three main producers (Electricité de France (EDF), Orano, French Alternative Energies and Atomic Energy Commission). The contracts include both and fixed costs and variable prices per cubic metre of disposal waste package. The long term monitoring costs are assigned to the main producers. Their share in these costs is based on the ratio of the final volume of waste packages delivered. The management of waste from medical or industrial uses is financed through fees paid by the corresponding waste producers based on a public price list.
Germany [101]	Federal states (Bundesländer) collect radioactive waste from the waste producers, which are charged a fee for handing over the waste ownership. From the fees thus collected, the Bundesländer finance the cost of the later disposal of the waste. In 2017, a law on the reorganization of responsibilities for nuclear waste management entered into force. This law regulates the conditions for implementing and managing a fund for interim storage and waste disposal in Germany. By paying US $30 billion into the fund, the operators of nuclear power stations transferred their responsibility and liability to the Federal Government.
Japan	Waste producers pay contributions in accordance with the amount of electricity generated by nuclear power for the disposal of HLW and long lived LLW. The contribution unit price is determined annually by the Government and the fee is levied on the electricity bill.

TABLE 17. EXAMPLES OF FUNDING THE DISPOSAL PROGRAMME VIA CONTRIBUTIONS FROM THE WASTE PRODUCERS (cont.)

	Funding
Republic of Korea [104]	Korea Hydro & Nuclear Power Company pays a quarterly contribution directly to the Radioactive Waste Fund according to the volume of spent fuel generated. The expenses producers of LLW and ILW pay to the Korea Radioactive Waste Agency (KORAD) depends on the volume of LLW and ILW transported to KORAD, which deposits the collected expenses into the Radioactive Waste Fund at the end of every month.
Netherlands [105]	All waste producers contribute to the fund for disposal of long lived waste, even if they produce only short lived LLW. The contributions for HLW and LLW and ILW are different. For LLW and ILW, there are fixed tariffs for specified categories of radioactive waste. However, the Central Organisation for Radioactive Waste has suffered losses for the management of LLW and ILW, which can be partly attributed to the successful implementation of waste separation and reduction policies. These policies included a financial incentive to reduce waste volumes, which in turn led to less, and ultimately insufficient, funding of the LLW and ILW repository operations.
Romania [67]	The operators of the Cernavoda nuclear power plant pay into a fund covering the costs of the disposal of spent fuel and radioactive waste. The fee was determined in 2007 and was set at US $2/MW·h.
Slovakia	The operator of the Bohunice and Mochovce nuclear power plants is obliged to pay annual fees to the National Nuclear Fund to cover the future costs of decommissioning, radioactive waste treatment from decommissioning and disposal of spent fuel and waste. The total annual fee for both plants amounted US $77 million in 2015. To cover the identified historical deficit in the National Nuclear Fund, an additional levy on electricity was introduced in 2012. Transmission and distribution companies transfer the collected proceeds to the Ministry of Economy and these are then transferred to the account of the National Nuclear Fund. In 2015, the total levy transferred was US $84 million.
Sweden [35, 48, 55, 106, 107]	Nuclear power plant operators pay a fee into a waste fund that has to cover the costs of decommissioning and waste management. The fee is based on the amount of electricity produced and was US $4/MW·h in 2016. For the nuclear power plant in Barsebäck, which is no longer in operation, the amount to be paid is fixed annually. The disposal of short lived operational waste from nuclear power plants is paid for directly by the power plant operators. Community benefits are also paid for directly by the waste producers and do not come from the fund that is used for the development and implementation of the disposal programme (see Section 5.2.2). Up until 2017, the nuclear power companies were also required to pay a special fee to finance the decommissioning of the research reactors in Studsvik and certain other costs of the early Swedish nuclear power programme. This fee amounted to US $0.30/MW·h. It is important to highlight that the responsibility for covering the costs remains with the waste producers until the end of the disposal programme and not until the end of the nuclear power plant's operating life.
United Kingdom [94, 108]	The national low level disposal facility operated by LLW Repository charges waste producers per waste container based on the waste volume, its weight, physical condition and radioactive content. For new nuclear reactors, the Government requires developers to establish funded decommissioning programmes prior to being given the go ahead to construct. The fund has to ensure that the developer pays for its share of the decommissioning and disposal of ILW and spent fuel in the GDF. The first payments into the fund are required before the plants go critical. A waste transfer price is negotiated between the developer and the Government in order to determine the likely price they will pay the Government for disposal. It also allows for the estimation of provisions which need to be put aside for that purpose.
United States of America [109]	Utilities producing spent fuel or HLW pay a fee into a fund to cover the disposal costs of those wastes. This fee was evaluated annually for sufficiency and was previously set at US $1/MW·h of nuclear power generated and sold. The fee was suspended in 2013.

Note: Waste producers' contributions are generally in the form of waste tariffs paid when handing over the waste to the WMO, a fee on the electricity price in the case of nuclear power plants or periodic payments that waste producers pay to the WMO. The Australian example examines whether waste disposal could be done as a commercial activity.

7.1.2. The State

In some cases, the State is the only available source of funding. This can happen at the early stage of the waste disposal programme when the WMO is being set up and when waste management systems and infrastructures are being developed. At that stage, resources for waste management might not be available, and the state budget may be the only practicable financial resource available.

Furthermore, when the waste owner is unknown or no longer exists, the responsibility for financing its management falls to the State (see also art. 21(2) of the Joint Convention [2]). Other scenarios are where only small waste producers are active that are not capable of bearing those costs, or where a country has phased out its nuclear activities and the resources set aside to cover the further waste management costs are insufficient.

Using the state budget for waste management might not in some of those cases seem to be fair, as it does not adhere to the 'polluter pays' principle. However, certain circumstances may justify such an approach on the basis that all citizens have an interest in the safe management and disposal of the waste. The State can fund the disposal programme via its annual state budget or via one or more endowments. An endowment is a lump sum that is paid for a specified purpose. Such a purpose might be the funding of the startup phase of the WMO when another funding mechanism has not been developed. The State can also financially support the disposal programme by providing guarantees (see Table 18). This can enable the WMO to get financial resources through bank loans or other financial instruments.

TABLE 18. EXAMPLES OF FUNDING THE DISPOSAL PROGRAMME FROM THE STATE BUDGET

	Funding
Canada [98, 111]	Examples of the long term safe management of legacy waste that is funded from the state budget are the Port Hope and Port Granby projects in Canada. The projects involve cleaning up historic LLW in Port Hope and Port Granby and the long term management of the waste. The Canadian Government has committed US $980 million to these projects.
Germany [101]	The funding of the decommissioning and waste management of the nuclear facilities and installations in the area of the public sector, primarily companies receiving government financing, is ensured through public budgets. As explained in Section 7.1.1, the Federal Government has been responsible for interim storage and waste disposal and the associated liabilities since 2017. In return for taking over those responsibilities from the nuclear power plant operators, the Government received a one-off payment of US $30 billion into a fund for the interim storage and disposal of the waste.
Hungary [110]	Waste producers contribute to a fund that covers the cost of managing the radioactive waste and spent fuel for the nuclear power plant operators. This fund also covers the cost of the disposal of legacy waste. The Government, however, also contributes, as it pays interest on the fund so that it will keep its value until the fund is completely used by 2084.
Lithuania [110]	The funds accumulated during the operation of the nuclear power plant were insufficient and the funding of the disposal programme is currently under consideration. Waste management is funded by the state budget and international assistance (e.g. European Union).

TABLE 18. EXAMPLES OF FUNDING THE DISPOSAL PROGRAMME FROM THE STATE BUDGET (cont.)

	Funding
United Kingdom [94, 112, 113]	Three situations exist in the United Kingdom: (a) When the UK nuclear industry was partially privatized in 1996, the Nuclear Generation Decommissioning Fund was set up with an initial government endowment of US $377 million to cover the costs of decommissioning and waste management. The fund was renamed the Nuclear Liabilities Fund in 2005 and valued at US $13 billion in March 2016. The Government will underwrite the Nuclear Liabilities Fund with respect to relevant liabilities of any fund shortfall. (b) For the 17 legacy sites managed by the NDA, the Government provides direct grant-in-aid of US $3.4 billion per year for the management of the waste, including the NDA share of the cost of a GDF. (c) As explained in Section 7.1.1, the Government requires developers to establish funded decommissioning programmes for new nuclear reactors to ensure the developer pays for its share of the disposal of ILW and spent fuel in the GDF. The cost of disposal is taken from the waste transfer price negotiated between the Government and the developer.

Note: Many countries have legacy waste and will fund the disposal of this type of waste from the state budget. An overview of funding schemes for radioactive waste and specifically of the funding mechanisms for legacy waste can be found in Ref. [110].

7.2. CONTRIBUTION PLAN

A fund contribution plan needs to be defined, the aim of which is to ensure that the fund will be sufficient to cover the disposal costs. The two components to the contribution plan for the fund are its target value (i.e. specifying how much funding will be needed) and the contribution schedule of the fund. As explained in Sections 7.2.1 and 7.2.2, specifying the target value and contribution schedule will require several assumptions and there are consequently significant uncertainties around the specified value and schedule. It is therefore necessary to revise the contribution plan periodically. Several States revise their waste fees or tariffs every three (Sweden) or five years (Belgium, Switzerland) [11, 114].

7.2.1. Target fund value

The estimated overnight cost is just one component in determining the target value of the fund. The overnight cost does not take account of the time at which the costs occur, and therefore ignores the effect of cost escalation and the time value of money.

Cost escalation is the change in the cost of specific goods or services over time. It includes the effects of inflation, but it also takes account of cost changes due to, for example, changes in productivity, technology or supply and demand on the market. In most countries, there are forecasting services that publish predictive escalation indices. These are typically prepared for a basket of goods for a particular market.

The time value of money refers to the concept that money available today is worth more than in the future due to its capacity to earn money through interest and investment. The discounted cost takes account of the effects of future price increases and the future value of money (see Table 19).

TABLE 19. ILLUSTRATION OF COST DISCOUNTING

	Example
Cost discounting	The assumption is made that an encapsulation plant will be built in 20 years with an overnight cost of an estimated US $100 million (i.e. if built now, it would cost US $100 million at today's price level). The cost is discounted to determine how much needs to be set aside today to fund the encapsulation plant in 20 years. It is assumed that the costs will rise at an annual rate of 1% over the next 20 years. The encapsulation plant will then cost US $122 million in 20 years at the price level of that year. It is also assumed that over those 20 years an annual financial return of 2% can be achieved on the provisions that are collected for funding the encapsulation plant. It can then be calculated that US $82 million is needed today to cover the US $122 million in 20 years. This amount — US $82 million — is the discounted cost of the encapsulation plant assuming a cost escalation rate of 1% and a 2% rate of return on the provisions over the next 20 years.

The discounted cost, also called the net present value of a cost item, can be calculated as follows:

$$\text{discounted cost} = \text{overnight cost} \times \left(\frac{1 + \text{annual escalation rate [\%]}}{1 + \text{annual discount rate [\%]}} \right)^{\text{time [years]}}$$

The discounted cost of the complete disposal programme is the sum of the discounted costs of the programme activities and items. This requires that those costs are distributed over the lifetime plan of the disposal programme. The lifetime plan shows when costs will occur and when resources for cost expenditures are needed. A hypothetical example of such a distribution is shown in Fig. 10. It is clear that the planning or schedule of the programme can have a large impact on the discounted cost. It is therefore important that sufficient attention is given to define a plan that is as accurate and as underbuilt as possible. The planning needs to be part of the baseline document that also describes the disposal programme for which the cost is estimated.

The discounted cost depends on the discount rate and the timing when the cost occurs. As the future discount rate and planning can only be assumed, the discounted cost is uncertain. This uncertainty can be very significant, in particular because of the sometimes very long timescales over which the discount rate needs to be assumed. The applied discount rate can therefore become a matter of much debate. The higher the assumed rate is, the lower the discounted cost and the smaller the contributions or provisions that need to be paid by the waste producers. If, on the other hand, the assumed discount rate is too high, the required amount of funding will be underestimated.

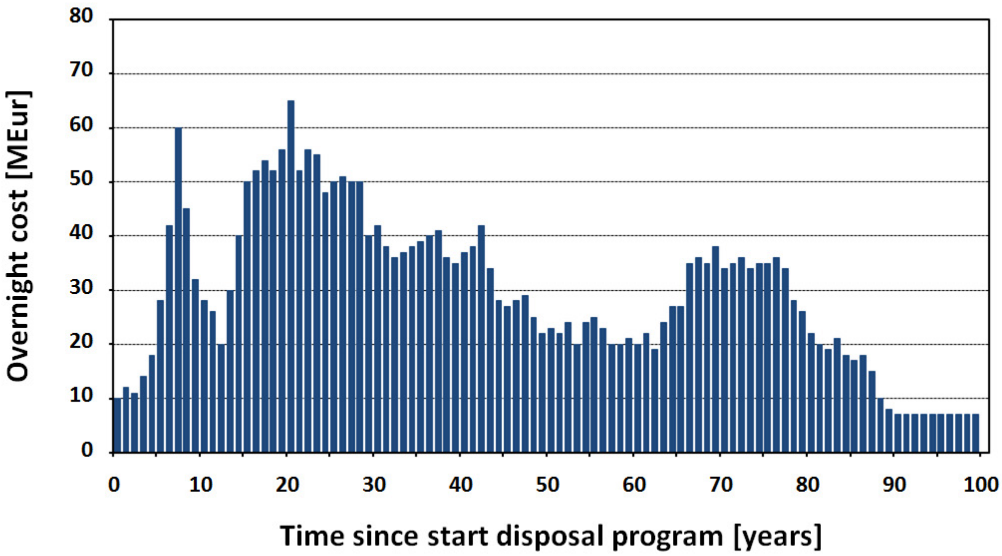

FIG. 10. Example of the distribution of overnight costs over the lifetime of a disposal programme.

As previously mentioned, one of the most significant uncertainties concerns the schedule or planning for the disposal programme because of the impact the time schedule has on the discounted cost. When a cost occurs at a later stage, the money set aside to cover it can earn interest and therefore fewer provisions need to be foreseen. This is of course only valid if the financial return on the provisions is larger than the cost escalation; otherwise the opposite is true.

The uncertainties around the discounted costs should be taken into account in the management of uncertainties and risks, as described in Section 6.1. Sensitivity analyses can be used to develop an idea of the sensitivity of the discount cost to the discount rate and planning. Furthermore, a good justification for the assumed discount rate should be provided, for example by having it assessed by an independent asset manager. The discount rate that can be assumed for a given fund will be linked to the investment strategy that is applied for the fund. A high risk investment strategy can result in a higher rate of return, but this needs to be balanced against the risks of such a strategy. The management and governance of the fund is further discussed in Section 7.2.2.

Because of the potentially large uncertainty surrounding the discounted cost, some States do not discount the cost and instead evaluate future liabilities based on what it would cost to meet them today. This avoids the risks of overestimating the discount rate, which would lead to insufficient funding. An advancement or deferral of the programme can also significantly change the funding estimate, which makes the discounted cost more vulnerable to a halt in the funding acquisition (e.g. because of a premature shutdown of the facility) and to financial crises.

Not to discount future costs is the more conservative approach, as it leads to a faster accumulation of provisions. The amount needed to cover a liability is gathered as soon as the liability appears. However, it renounces the opportunities which could be exploited with an efficient investment strategy. Discounting the cost also reflects an economic reality, as money today is worth more than it will be tomorrow. Therefore, valuing an asset or liability by its future (or nominal) value can be misleading.

Which method is chosen (i.e. whether or not to discount the cost) often depends on the prevailing legislation and accounting practices (see Table 20). If provisions are tax deductible, it can be worthwhile to set up these provisions faster. The interest generated by the provisions might, on the other hand, be subject to taxation as well.

TABLE 20. EXAMPLES OF DISCOUNT APPROACHES

	Approach
Australia [73]	The cost estimate for the spent fuel and ILW repository in South Australia assumes discount rates of 4% and 10%. These reflect discount rates commonly used for investments made by either public or private entities. They result in discounted costs of US $34 billion and US $10 billion, respectively.
Belgium [116]	In order to take into account the time value of money and the opportunity cost of capital, the fees are increased above inflation each year by a constant interest rate fixed at 1% in real terms. This corresponds to the net discount rate applied by ONDRAF/NIRAS for net present value estimates of its future storage and disposal costs.
Canada	The funding requirement is based on the discounted future cost of the project. The rates of returns applied are the best estimates by the waste owners (4–6%), with inflation assumptions based on long term published forecasts of labour, materials and consumers price indices (2–4%).
Finland [100]	The funding system is based on undiscounted costs. Money deposited into the fund gains interest every year, which reduces the annual amount of new funding required.

TABLE 20. EXAMPLES OF DISCOUNT APPROACHES (cont.)

	Approach
France [117]	The discount rate used by the operators is regulated to ensure that the nominal discount rate does not exceed a cap fixed by the ministers for economy and for energy. It is adjusted for inflation based on the long term inflation objective of the European Central Bank. The gross value of the total future costs of decommissioning, spent fuel management and the long term management of radioactive waste for the three main operators (EDF, Orano, French Alternative Energies and Atomic Energy Commission) were assessed in 2010 at US $99 billion (undiscounted). A nominal discount rate of 5% was adopted, which is slightly lower than the capped rate. Based on an inflation average of 2%, the true discount rate is 3%. Taking account of that discount rate, the discounted costs of decommissioning, spent fuel management and the long term management of radioactive waste for the three main operators amount to US $48 billion. The sensitivity of these provisions to the discount rate variation is also evaluated. A reduction of 0.5% in the discount rate resulted in an increase in discounted nuclear provisions of over US $4.4 billion, which represents around 10% out of the total of US $48 billion. As expected, the variation impact is greatest for provisions with a long maturity date.
Japan	The assumed discount rate is based on the consumer price index and government bonds for ten years and was 1.0% in 2015 and 0.9% in 2016. The figures for the consumer price index and government bonds for ten years are published periodically by the Japanese Government.
South Africa [70]	An 8% rise in costs and an investment return of 10% are assumed for the cost estimate of the Vaalputs repository for LLW and ILW.
United States of America [79]	In its assessment of the adequacy of the fee being paid by nuclear power utilities for the permanent disposal of their spent fuel and HLW, the USDOE uses seven interest and inflation rate forecasts from five separate sources to characterize the uncertainty inherent in projecting long range economic conditions.

Note: Examples of applied discount rates can be found in Refs [11, 115]. When comparing discount rates, it is important to check whether the real or nominal discount rate is given. Nominal discount rates are not adjusted for inflation, while real rates are. As a result, nominal rates are almost always higher, except during rare periods of deflation (i.e. negative inflation). States which do not discount the cost of disposal, decommissioning or waste management include Finland and South Africa. Some of the examples presented below show the impact of the planning and assumed discount rate on the discounted cost.

7.2.2. Contribution schedule

After the target fund value is determined, the schedule by which the contributions will meet the target needs to be specified. This requires knowledge of the total waste inventory that will be disposed of, the duration of the waste producing activities or the amount of (future) nuclear electricity generation. This information might not be available and might need to be assumed. In cases where annual contributions will be paid into the fund based on an assumed operating lifetime of the facility generating radioactive waste, the most straightforward contribution schedule is a constant one. This means that the contribution will be the same for every year of the facility lifetime.

The target value of the encapsulation plants in the example in Section 7.2.1 is US $122 million in 20 years. In cases where a constant annual contribution schedule is applied over those 20 years, and assuming a yearly return on investment of 2%, the annual contribution would be US $5 million. This amount is calculated with the sinking fund factor (SFF). This is a factor which needs to be multiplied by the target fund value to compute the uniform stream of periodic contributions needed to fund that target in n periods if contributions earn a periodic return of r:

$$\mathrm{SFF} = \frac{r}{(1+r)^n - 1}$$

More information on the mathematics behind contribution schedules can be found in Ref. [118] (see Table 21).

TABLE 21. EXAMPLES OF FUND CONTRIBUTION SCHEMES

	Scheme
Canada [6]	OPG builds up the funds for the management of the spent fuel over a period of approximately ten years.
Finland [11, 119, 120]	The funding for waste management costs can be distributed over a period of 40 operating years. The scale of the companies' future liabilities is assessed every three years by Posiva on the hypothetical basis that the plants will close at the end of that year.
Sweden [35, 48]	Since 2017, the calculation of the fees for Sweden's nuclear power plants has been based on an operating time of 50 years for each of the reactors that are in operation. Previously, the operating time for the calculation of fees and guarantees was 40 years. It is also stipulated that the minimum remaining operating time will be six years. This does not apply if it can be assumed that the operating period could cease before then. Licensees of nuclear facilities other than nuclear power reactors base their cost estimates and the funding buildup on the expected remaining period of operation.
United Kingdom [121]	In the case of the funding mechanism for the decommissioning and waste management set-up for Hinkley Point C, the liabilities will be sufficient after a period of 37 years of the 60 year operational period.

Facility lifetime might be shorter or future waste volumes lower than anticipated and this risks resulting in insufficient funding. This risk might even be self-inflicted for volume based tariffs, as these are likely to result in smaller volumes of waste being produced.

This risk of insufficient funding can be reduced by a 'front end loaded' contribution schedule. In such a schedule, more is contributed at an earlier period than in a constant schedule. The fund can, for example, be collected over a shorter period than the expected lifetime of the nuclear activities or, in a more extreme case, by a prepayment before the startup of the facility. Using the encapsulation plant example again, in the case of a prepayment, an amount of US $82 million would be needed. If the contributions are collected over the first five years instead of 20 years, the annual contributions would amount to US $17 million.

A sensible approach could be to follow a front end loaded schedule to fund the fixed costs of the disposal programme while applying a constant one for the costs that vary with the amount of waste. This could ensure that, if less waste is generated than anticipated, the funding for the fixed costs has already been gathered. The funding for the variable costs will be lower due to the lower amount of waste, but so will be the variable costs themselves.

7.3. FUND MANAGEMENT

The waste producers' contributions can be collected in a fund or the anticipated disposal costs can be included on the company's balance sheet as a liability. A fund is commonly set up for funding costs that lie far in the future, such as the disposal of HLW or the post-closure phase of the disposal project. The time span between the acquisition of the funding and the time when the actual expenses arise offers the possibility of taking advantage of the time value of money in the fund. However, it also entails the risk of mismanagement or even misuse of the fund. Examples exist of pension funds or funds dedicated to maintenance that were used for other purposes. The fund thus needs to be managed properly, which requires specifying the ownership of the fund and establishing a suitable investment strategy.

7.3.1. Fund ownership

Different models of fund ownership exist, and a distinction is made between internal and external funds. Internal funds are managed by the waste producers; while external funds are managed by an organization separate and independent from the waste producers, such as the WMO or government. An external fund offers a transparent model that facilitates verifying whether the financial resources are available, adequate and used for the intended purpose. It also offers protection against a loss of funding in the case of operator bankruptcy. In the case of an internal fund, it can be a segregated or ring fenced fund, which means that it can only be used for the purpose for which it is set aside.

A distinction can be made between a centralized fund for the entire industry or for decentralized funds, of which are as many as there are operators. In some countries, the funds for waste management and decommissioning activities are merged into one single fund (see Table 22).

TABLE 22. EXAMPLES OF FUND OWNERSHIP

	Fund ownership
Belgium [62, 116]	The medium term and long term funds for waste management are segregated funds managed by ONDRAF/NIRAS. ONDRAF/NIRAS may, following agreement by the minister of economic affairs, manage a fund to finance its long term duties, particularly waste disposal. The waste producers pay contributions to the fund, in accordance with the rules approved by the Board of Directors of ONDRAF/NIRAS and the minister of economic affairs. The use of this fund is audited regularly by a special monitoring committee.
Canada [98]	Owners of spent fuel have been required to establish segregated funds for the long term waste management of the spent fuel since 2002. Some owners had already created segregated funds earlier.
France [11]	The waste management fund is an internal segregated fund. Nuclear power plant operators allocate provisions for the management of spent fuel and radioactive waste. The Government, however, assesses the adequacy and security of the funding.
Hungary [122]	The Central Nuclear Financial Fund is a separate state fund that is exclusively earmarked for financing the decommissioning of nuclear facilities, the interim storage of the radioactive waste and the construction and operation of waste disposal facilities. The fund is managed by the Hungarian Ministry of National Development.
Japan	NUMO, the WMO, collects fund contributions every year from waste producers such as the owners of power plants. These contributions are then deposited into an external fund, which is managed by an independent organization, the Radioactive Waste Management Funding and Research Center.
Slovakia	The National Nuclear Fund is 100% government owned, and part of the public finance system has the role of collecting funds for the future financing of decommissioning activities and final disposal of radioactive waste and spent fuel.
Sweden [106]	The disposal fund is an external fund. The fees paid by the different waste producers are earmarked and may only be used to cover the costs attributable to that particular waste producer. If the fees paid in by a reactor owner are insufficient to cover the payer’s costs, fees paid in by another reactor owner may not be used to make up the difference. A separate authority, the Nuclear Waste Fund, which is a government authority, controls and manages the fund. The Swedish Radiation Safety Authority, and in certain cases the Government, approve disbursements from the fund.
Switzerland	For the costs arising after the closure of nuclear power plants, the owners set aside provisions in an external fund managed by the commission STENFO (Stilllegungs- und Entsorgungsfonds), which is under the supervision of federal authorities. Costs arising before closure are paid directly by the owners and corresponding internal provisions are made.
United Kingdom [113]	Developers of new nuclear power plants are required to establish funds for decommissioning and waste management prior to being given the go ahead to construct. Those funds have to be independent from the operator and protected from the operator’s creditors. An individual utility is free to maintain one fund for its fleet, or one fund for each reactor in the fleet. EDF Energy’s decommissioning and waste management liabilities for its advanced gas cooled reactors and pressurized water reactors are met from the Nuclear Liabilities Fund. It is wholly owned by the Nuclear Trust and comprises five trustees, three of which are appointed by the secretary of state and two by EDF Energy. The trustees are also executive directors of the Fund. Payments from the fund to EDF Energy are made on application to the NDA.

Note: An overview of the ownership of decommissioning and waste management funds in EU Member States can be found in Ref. [115].

7.3.2. Investment strategy

The growth of the fund depends on the investment strategy. The fund resources may be invested in industrial or public activities, including company shares and corporate or governmental bonds.

A greater return on investment will result in a smaller need for contributions from the waste producers or the accumulation of a larger reserve. It is, on the other hand, important to protect the capital in the fund by following a sufficiently conservative strategy. It will be required to find the right balance between both perspectives. This can be achieved by following a cautious and diversified investment strategy. The resources can for example be deposited in the national account or invested in government bonds. Nevertheless, even these 'safer' options do not entirely protect against the financial uncertainties and instabilities of the economic situation in any country.

On the other hand, there is the risk that the return on the investment might be lower than anticipated when discounting the disposal programme's cost (see Section 7.1). This might lead to insufficient funding to cover the cost of the disposal programme. It is therefore necessary to assume a return on investment that is realistic for low risk investments.

Another risk that needs to be considered when investing the fund resources is the liquidity risk. As the exact dates of the programme planning are unknown, the timing when the resources need to be available is uncertain. Careful consideration of the disposal programme planning is therefore needed when investing the resources. A portfolio manager can be appointed to manage the fund in line with any defined requirements on the investment strategy (see Table 23).

TABLE 23. EXAMPLES OF FUND INVESTMENT STRATEGIES AND RESTRICTIONS

	Strategies and restrictions
Czech Republic [115]	The funds at the Nuclear Account may be invested in financial markets in liquid government bonds, the Czech National Bank and securities of emitters selected by the Ministry of Finance.
Finland [11, 100]	A maximum of 75% of the Nuclear Waste Management Fund can be lent back to the operators, who in return need to pay a government fixed amount of interest.
Netherlands [123]	The Central Organisation for Radioactive Waste, the state owned WMO, is responsible for the capital growth of the fund. The money in the fund is put in safe investments (e.g. government bonds) which have to be approved of by the minister of economic affairs.
Sweden [48]	Assets in the waste fund are managed to ensure a good return and satisfactory liquidity. The fund assets are deposited in an interest bearing account at the National Debt Office, in treasury bills issued by the government or in covered bonds. Since 2017 regulation also allows that a part of the fund can be invested in shares and corporate bonds.

Note: An overview of the investment portfolios of decommissioning and waste management funds in EU Member States can be found in Ref. [115].

8. CONCLUSIONS

A methodology has been presented on how to estimate the cost of a disposal programme, either surface or geological, and what mechanisms can be used to fund the programme. It is, however, important to acknowledge that developing such estimates and funding schemes is a specific and complex task that requires specific expertise. Experts in this field are best placed to perform or support these tasks and to have the cost estimate reviewed by external experts.

The key to developing a cost estimate for a disposal programme is having an adequate understanding of the programme and the purpose of the estimate. These should be clearly documented in a baseline document. The baseline document will serve as the basis for the cost estimate. It describes the disposal programme and its scope, and outlines what is to be included in or excluded from the estimate. It thus provides traceability and will aid in justifying the assumptions and principles that underlie the estimate.

A disposal programme often faces many unknowns and parts of it cannot be specified. It is nevertheless important to try to develop a baseline description that covers all aspects of the disposal programme and is as complete as possible. This will require that various assumptions are made about the unknowns within the programme, including the justification for the assumptions.

Once the programme's baseline has been defined or, to some extent, assumed, the programme's cost can be estimated. A rough and first idea of the cost of such a programme can be obtained by using the cost of a similar programme and adjusting for differences. However, a more precise estimate requires a WBS dividing the programme into a series of smaller and more specific components.

Next, the costs of the WBS items are assessed. This requires the development of a cost database in which all quantities or durations and the estimated unit costs of the items in the WBS are compiled. The database forms the foundation of the estimate and its quality will determine that of the overall cost estimate. It will be crucial to record and keep track of the sources for the cost data and document how cost data are adapted, scaled or indexed, and which assumptions might be made when using or adapting the cost data. Future cost estimates will benefit from such records.

Given the usually very long time span for implementing a disposal programme, its complexity and the involvement of many stakeholders, the uncertainties surrounding the cost estimate are generally large. Moreover, there is a significant risk that the disposal programme will be altered or even overturned. It is therefore important to identify those uncertainties and risks and ensure that they are reflected in the cost estimate. This is no easy task, but it is a crucial aspect of a cost estimate and should receive sufficient attention.

An approach to dealing with uncertainties and risks usually consists of (one of the) following elements:

— Identifying the uncertainties and programme risks;
— Developing a range of possible cost outcomes by performing sensitivity and scenario analyses;
— Developing a risk management framework to mitigate the potential impact of the risks;
— Ensuring that provisions are set aside to cover the cost impact of the uncertainties and risks.

Finally, mechanisms for funding the disposal programme need to be established. Different mechanisms for funding disposal programmes are used worldwide. Selecting the most suitable funding mechanism for the disposal programme depends on many factors, such as the nuclear strategy and policy in the country, disposal option, legislative background and institutional framework. A country with operating nuclear power plants will probably adopt a different funding mechanism than a country with only institutional waste.

There might be a long time span between the acquisition of the funding and the time when the actual expenses arise. This offers the possibility to take advantage of the time value of the money in the fund by earning interest from investments in financial products. A greater return on investment will result in a smaller need for contributions from the waste producers or the accumulation of a larger reserve. It is, on the other hand, important to protect the capital in the fund by following a sufficiently conservative strategy. It will be necessary to find the right balance between both perspectives. Furthermore, the fund needs to be protected against the risk of mismanagement or even misuse. It is thus important that the management of the fund is properly thought through and, possibly, regulated.

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Annex

PURCHASING POWER PARITIES

Currency conversion to US dollars is done using purchasing power parities (PPPs)[1]. The Organisation for Economic Co-operation and Development (OECD) states that[2] "In their simplest form, PPPs...show the ratio of the prices in national currencies of the same good or service in different countries. PPPs are also calculated for product groups and for each of the various levels of aggregation up to and including GDP." The basket of goods and services priced is a sample of all those that are a part of final expenditure: household consumption, government services, capital formation and net exports, covered by GDP. This indicator is measured in terms of national currency per US dollar. The conversion rates published by the OECD for 2016 were used. These are included in Table A–1. For countries in the euro area one single conversion factor is used. The reference years of the costs included in the publication are not mentioned, so as not to burden the text too much.

1 See https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm

2 See www.oecd.org/sdd/purchasingpowerparities-frequentlyaskedquestionsfaqs.htm

TABLE A–1. CONVERSION RATES USED IN THIS PUBLICATION

	Conversion to US dollars
Australia	1.5
Bulgaria	0.7
Canada	1.3
China	3.5
Czech Republic	13
Euro area*	0.8
Hungary	135.2
Japan	100.3
Republic of Korea	874.6
Poland	1.8
Romania	1.7
Russian Federation	23.7
South Africa	5.9
Sweden	9.1
Switzerland	1.2
United Kingdom	0.7
United States of America	1

* Austria, Belgium, Cyprus, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Portugal, Slovakia, Slovenia and Spain.

ABBREVIATIONS

Andra	National Radioactive Waste Management Agency
ARAO	Agency for Radwaste Management
EDF	Electricité de France
EPRI	Electric Power Research Institute
GDF	geological disposal facility
HLW	high level waste
ILW	intermediate level waste
JAVYS	Nuclear and Decommissioning Company
LLW	low level waste
NDA	Nuclear Decommissioning Authority
NWMO	Nuclear Waste Management Organization
OECD	Organisation for Economic Co-operation and Development
OECD/NEA	OECD Nuclear Energy Agency
ONDRAF/NIRAS	Belgian Agency for Radioactive Waste and Enriched Fissile Materials
OPG	Ontario Power Generation
PPP	purchasing power parity
RD&D	research, design and development
RWM	Radioactive Waste Management Ltd
SERAW	State Enterprise Radioactive Waste
SKB	Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering AB)
SÚRAO	Radioactive Waste Repository Authority
URL	underground research laboratory
USDOE	United States Department of Energy
USGAO	United States Government Accountability Office
VLLW	very low level waste
VSLW	very short lived waste
WBS	work breakdown structure
WIPP	Waste Isolation Pilot Plant
WMO	waste management organization

CONTRIBUTORS TO DRAFTING AND REVIEW

Aguilar, O.M.	Ministry of Energy, Mexico
Aikas, T.	Posiva, Finland
Amjid, A.	Pakistan Atomic Energy Commission, Pakistan
Bajorinas, V.	State Enterprise Radioactive Waste Management Agency, Lithuania
Bajpai, R.K.	Bhabha Atomic Research Centre, India
Bilal, S.	Federal Authority for Nuclear Regulation, United Arab Emirates
Biurrun, E.	DBE Technology GmbH, Germany
Boelen, J.	Central Organisation for Radioactive Waste, Netherlands
Bollingerfehr, W.	DBE Technology GmbH, Germany
Caballero, D.H.	National Atomic Energy Commission, Argentina
Carolissen, A.	National Radioactive Waste Disposal Institute, South Africa
Chen, L.,	Beijing Research Institute of Uranium Geology, China
Chivu, I.R.	Nuclear Energy & Radioactive Waste, Romania
Daniška, V.	DECOM, Slovakia
Dardour, S.	International Atomic Energy Agency
Dias, A.F.	National Nuclear Energy Commission, Brazil
Dima, M.A.	Nuclear Energy & Radioactive Waste, Romania
Duda, V,	SÚRAO, Czech Republic
Ferlat, F.	Andra, France
Fernando, K.	Australian Nuclear Science and Technology Organisation, Australia
Feshchenko, V.	Kyiv National Economic University, Ukraine
Getman, Y.	State Agency of Ukraine on Exclusion Zone Management, Ukraine
Gupta, S.	Bhabha Atomic Research Centre, India
de Guzman, A.	Department of Energy, Philippines
Hardin, E.	Sandia National Laboratories, United States of America
Holmberg, P.-A.	Swedish Nuclear Fuel and Waste Management Company, Sweden
Jackson, I.	Jackson Associates, United Kingdom
Jobse, A.P.	NV EPZ, Netherlands
Katsva, M.	International Atomic Energy Agency
Kegel, L.	Agency for Radwaste Management, Slovenia

Keto, J.	Ontario Power Generation, Canada
Kitagawa, Y.	Nuclear Waste Management Organization of Japan, Japan
Korczyc, A.	Radioactive Waste Management, Poland
Kostadinova, K.	Ministry of Energy, Bulgaria
Kukina, S.	NO RWM FSUE, Russian Federation
Laction, L.	Nuclear Energy & Radioactive Waste, Romania
Mathieson, J.	Nuclear Decommissioning Authority, United Kingdom
Mayer, S.	International Atomic Energy Agency
McMinn, M.	Radioactive Waste Management Ltd, United Kingdom
Morales, E.	Department of Energy, Philippines
Nastase, D.V.	Nuclear Energy & Radioactive Waste, Romania
Navarro, M.	ENRESA, Spain
Poskas, G.	Lithuanian Energy Institute, Lithuania
Potier, J.M.	Consultant, France
Raiets, M.	State Agency of Ukraine on the Exclusion Zone Management, Ukraine
Rodriguez, J.M.	Swiss Federal Office of Energy, Switzerland
Sanchez-Valdepeñas, L.A.	ENRESA, Spain
Sekerbayeva, S.	Kazatomprom, Kazachstan
Siginevich, D.	Rosenergoatom, Russian Federation
Slugen, V.	National Nuclear Fund of Slovak Republic, Slovakia
Taylor, J.	Department of Industry, Innovation and Science, Australia
Tsumoto, A.	Nuclear Waste Management Organization of Japan, Japan
Van Heek, A.	International Atomic Energy Agency
Van Marcke, P.	International Atomic Energy Agency
Warren, P.	International Atomic Energy Agency
Woodruffe, A.	Federal Authority for Nuclear Regulation, United Arab Emirates
Yordanov, I.	Ministry of Energy, Bulgaria
Zlobenko, B.	Institute of Environmental Geochemistry, Ukraine

Consultants Meetings

Vienna, Austria: 21–24 May 2013, 9–13 November 2015, 31 October–4 November 2016, 5–9 February 2018

Technical Meetings

Vienna, Austria: 30 May–3 June 2016, 22–26 May 2017

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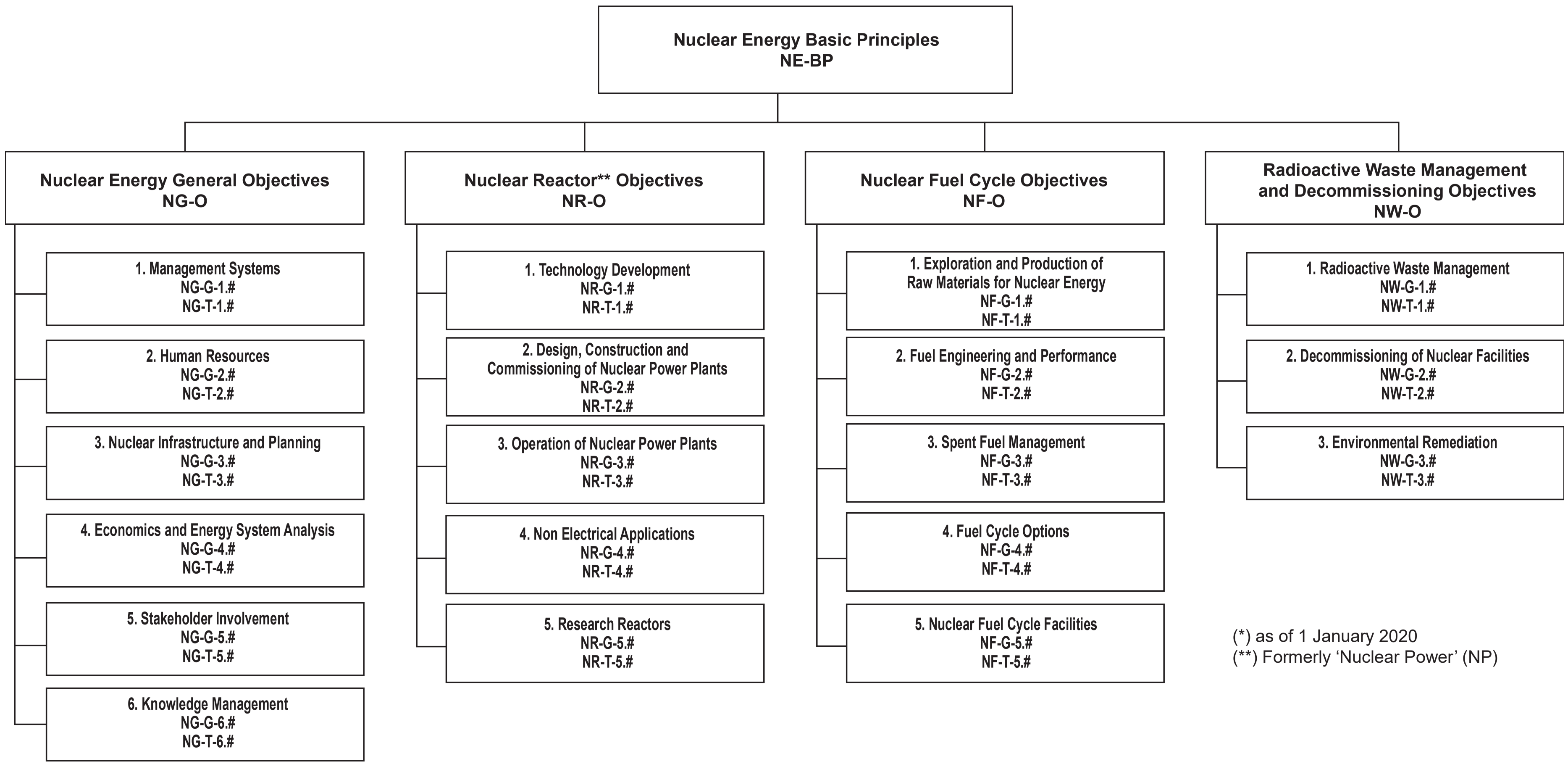

(*) as of 1 January 2020
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BP:	Basic Principles
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T:	Technical Reports
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