IAEA Nuclear Energy Series

No. NW-T-1.24 (Rev. 1)

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Options for Management of Spent Nuclear Fuel and Radioactive Waste for Countries Developing New Nuclear Power Programmes

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OPTIONS FOR MANAGEMENT OF SPENT NUCLEAR FUEL AND RADIOACTIVE WASTE FOR COUNTRIES DEVELOPING NEW NUCLEAR POWER PROGRAMMES

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IAEA NUCLEAR ENERGY SERIES No. NW-T-1.24 (Rev. 1)

OPTIONS FOR MANAGEMENT OF SPENT NUCLEAR FUEL AND RADIOACTIVE WASTE FOR COUNTRIES DEVELOPING NEW NUCLEAR POWER PROGRAMMES

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

Today, numerous countries are considering construction of their first nuclear power plant or the expansion of a small nuclear power programme, and many of these countries have limited experience in managing radioactive waste and spent nuclear fuel. They often have limited information about available technologies and approaches for safe and long term management of radioactive waste and spent nuclear fuel arising from power reactors. The lack of basic know-how and of a credible waste management strategy could present a major challenge or even an obstruction for countries wishing to start a nuclear power programme.

The IAEA has published guidance on particular elements of radioactive waste and spent fuel management, such as establishing nuclear technical and regulatory infrastructure, relevant financing schemes, national policy and strategies, multinational approaches, and other aspects linked to building nuclear power plants. The present publication is a revision of the 2013 version of IAEA Nuclear Energy Series No. NW-T-1.24, developed to provide a concise summary of key issues relating to the development of a sound radioactive waste and spent nuclear fuel management system. This revision updates the original 2013 publication to include some new information and to provide greater clarity.

This publication provides information for countries with small or newly established nuclear power programmes on the challenges of, and current and potential alternatives for, managing reactor waste and spent fuel arising during operation and decommissioning of nuclear power plants. The publication primarily focuses on current technical options but also considers possible future developments and discusses relevant legal, political, technical and safety issues. It identifies the role of the international community, including the IAEA, in supporting the responsible introduction of nuclear power in interested countries and potential actions to be adopted.

The IAEA expresses its thanks to all those who were involved in the preparation of this publication and its revision, especially C. McCombie (Switzerland), who was the principal drafter. The IAEA officers responsible for this publication were L. Nachmilner, for the original publication, and I. Mele, for the revision, both of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Today, there is a growing demand for nuclear power, driven mainly by the desire for additional electrical energy produced by low carbon technology. Most emphasis is placed on construction and operation of nuclear power plants. An important lesson from the period of nuclear expansion a few decades ago is, however, that the issue of waste and spent fuel management should not be neglected, since it influences both the economics and the public acceptance of nuclear power.

The future management of spent nuclear fuel (SNF) and radioactive waste from nuclear energy production is a major challenge and a possible obstruction for countries wishing to start a nuclear power programme. In addition, for countries with small or newly established nuclear power programmes, the timescales on which disposal facilities are required may differ from those of countries with large, established nuclear power programmes, so that long term strategic planning needs to be adapted appropriately. The timescale from starting up a nuclear power plant through to finally disposing of all waste that it produces can be a hundred years or more. Nevertheless, it is important that a credible strategy, technical plans and methods for their financing exist from the outset for carrying out all future actions in a manner that ensures safety and security at all times. These plans may be adapted as new technologies appear, but they are at all times to be based on proven technologies. It may also be prudent to keep open alternative options that are to be narrowed down at future decision points. This publication lays out strategic and technical options for spent fuel and radioactive waste management based on experience gathered to date in mature nuclear power programmes.

1.2. USERS

This publication is aimed at those responsible for planning the introduction of nuclear power into a national energy programme. As the guidance provided is also relevant for countries with small nuclear power programmes, and, in its general aspects, also for countries operating just research reactors, it is also addressed to decision makers involved in the planning of waste and spent fuel management in their countries. In all cases, the policies and strategies being followed by large nuclear countries need to be adapted for the specific conditions of small programmes, most obviously with regard to the appropriate timescales for implementation of all necessary facilities, including waste repositories.

1.3. OBJECTIVES

The objectives of the publication are:

- To describe the challenges associated with the safe, environmentally sound and economical management of spent fuel and different types of radioactive waste generated in connection with operation of a nuclear power plant;
- To provide a background for establishing a national policy and technical strategies for managing spent fuel and radioactive waste from nuclear power plants;
- To identify existing waste and spent fuel management strategies and possible future developments, including multilateral or regional solutions;
- To highlight the legal, political, economic and technical requirements contributing to a safe, feasible and acceptable implementation for each of these options;
- To formulate, for countries with small or newly established nuclear power programmes, key messages and recommendations whose serious consideration will help these countries address the challenges associated with expanding nuclear power in a safe, secure and economical manner;
- To identify future actions that could help countries with small or newly established nuclear power programmes move towards implementation of national and/or multilateral solutions to management of waste associated with nuclear power plants.

1.4. SCOPE

Radioactive waste is any material for which future use is not anticipated and which contains, or is contaminated with, radionuclides at activity concentrations above clearance levels established by a regulatory body. Thus, SNF is considered as radioactive waste if intended to be directly disposed of, but as secondary raw material when directed to reprocessing. Radioactive waste that has been cleared or exempted by the regulator's decision is not subjected to supervision of the nuclear regulatory body, but it still needs to be managed in accordance with non-nuclear legislation.

Radioactive waste has to be managed under nuclear regulatory control. Its management consists of all activities, administrative and operational, that are involved in the handling, pre-treatment, treatment, conditioning, transport, storage and disposal of radioactive waste.[1]

This publication covers current management options for SNF, waste from reactor operation, waste from decommissioning and waste from reprocessing and recycling of nuclear fuel. Although it deals with all waste categories, more weight is placed on long lived waste and spent fuel, since the timescales, the technological challenges and the financial resources required for safe management of these are larger than for other waste types. Although waste from other nuclear activities (industrial, medical and scientific) also needs to be considered, such waste is not the focus of this publication.

The scope is limited to waste from currently available reactor types, mainly light water reactors (LWRs) and heavy water reactors (HWRs). In the reprocessing scenario, the recycling of uranium and plutonium in fast reactor systems is indicated as a technical option. However, as it is anticipated to be commercially available only after the mid twenty first century, it is not topical for new programmes, and waste from such reactors is not covered here.

Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.5. STRUCTURE

Section 2 presents a brief review of existing advisory guidance on policies, strategies and programmes for management of spent fuel and radioactive waste. Section 3 summarizes waste and spent fuel inventories that arise from the nuclear fuel cycle. The descriptions are structured according to the waste source, since this is how newcomers will first encounter such information. Section 4 then presents an overview of the management practices required for the storage and disposal of the waste. The aim of these sections is to provide strategic and technical information on managing the various waste streams produced in nuclear power production at the depth required for decision makers to understand the overarching management strategies that are discussed in Sections 5 and 6. Section 5 discusses the need for an integrated approach to managing all waste that will arise. Section 6 then proposes a range of possible strategies which reflect national choices to be made by countries embarking on nuclear power, and examines, with the aid of an associated annex, the political, legal, societal, economic and technical challenges associated with each strategic option. Finally, Section 7 concludes with overarching strategic guidance on how a country embarking on a nuclear power programme might address the challenges relating to spent fuel management, specific comments on the transition from a non-nuclear power country, and specific recommendations on what steps can be carried out to ensure that this transition is smooth and safe. The current waste management approaches of relevant countries are summarized in the annexes.

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[1] Exact definitions for the terms used can be found in INTERNATIONAL ATOMIC ENERGY AGENCY, Radioactive Waste Management Glossary: 2003 Edition, IAEA, Vienna (2003).

2. STRATEGIC APPROACHES OF INTERNATIONAL ORGANIZATIONS

2.1. JOINT CONVENTION AND SAFETY STANDARDS

The IAEA strongly recommends that Member States join the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [1], which is the highest level agreement laying out how Member States should organize their programmes and which is binding on signatories. Its purpose is to achieve and maintain a high level of safety in spent fuel and radioactive waste management, through the enhancement of national measures and international cooperation. It focuses, however, on principle aspects, so that further guidance on implementation of infrastructure and procedures is necessary. This is provided in a number of IAEA publications, of which the key reports are described below.

In order to ensure that the radioactive waste in any country is managed safely, so that individuals, society and the environment are adequately protected against radiological and other hazards, it is necessary to have an established legislative and regulatory framework and to create the necessary organizations for implementation and oversight of waste management operations and facility development, as stated in the Joint Convention. The prime objective of the Joint Convention, which entered into force in 2001 and which in March 2017 had 75 Parties and 42 Signatories, is to ensure that the signatories take adequate responsibility for ensuring proper organization of the activities connected to spent fuel and radioactive waste management so that people and the environment are protected. The Joint Convention also recognizes [1]:

> "that radioactive waste should, as far as is compatible with the safety of the management of such material, be disposed of in the State in which it was generated, whilst recognizing that, in certain circumstances, safe and efficient management of spent fuel and radioactive waste might be fostered through agreements among Contracting Parties to use facilities in one of them for the benefit of the other Parties, particularly where waste originates from joint projects."

Article 19(2) of the Joint Convention states that [1]:

> "This legislative and regulatory framework shall provide for:
>
> (i) the establishment of applicable national safety requirements and regulations for radiation safety;
> (ii) a system of licensing of spent fuel and radioactive waste management activities;
> (iii) a system of prohibition of the operation of a spent fuel or radioactive waste management facility without a licence;
> (iv) a system of appropriate institutional control, regulatory inspection and documentation and reporting;
> (v) the enforcement of applicable regulations and of the terms of the licences;
> (vi) a clear allocation of responsibilities of the bodies involved in the different steps of spent fuel and of radioactive waste management."

A key element of the Joint Convention is the requirement on Contracting Parties to produce national reports that illustrate how the objectives of the Convention, especially a high level of safety in spent fuel and radioactive waste management, have been achieved [2]. These reports are reviewed at three year intervals, and valuable feedback is given to the submitting country.

Establishing the implementing and regulatory organizations that will be responsible for all aspects of waste management is a larger task. The organizational structures that have been established vary from country to country. It is essential to allocate the functions required by the Joint Convention to specific bodies and to ensure that the proper degree of oversight and independent review of all activities is guaranteed. A key decision at the highest level is who has direct responsibility for regulation and implementation of waste management practices, and most particularly of waste disposal. In all countries, the former task is a government responsibility. In many countries, the implementation task is also tackled by the government or one of its agencies but, in others, implementation is the responsibility of the waste producers. This can be carried out directly by making the nuclear power plant owners responsible, but often these owners join forces to form a dedicated waste management organization, as is the case in Finland (Posiva), Sweden (SKB) and Switzerland (Nagra). Even if the waste management organizations are established by the government, the financing is normally provided by the waste producers. Examples here are France (Andra), Hungary (PURAM), Japan (NUMO) and Slovenia (ARAO). Some established nuclear power programmes have developed and adapted their structures for regulation and implementation as the programmes have matured.

In addition to the guidelines regarding the form and structure of national reports [2] which are of particular relevance to countries with small and newly established nuclear power programmes, the IAEA publishes safety standards aimed at providing all Member States with harmonized instructions or guidance on establishing and maintaining high levels of safety in all nuclear activities, including the management of all types of radioactive waste. These commence with a high level publication on, IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [3], and cover a range of thematic issues and facility specific guidance. Radioactive waste management (RWM) is one of the themes, and an IAEA safety standard covers RWM facilities.[2]

In 2006, the IAEA launched the IAEA Nuclear Security Series, in which more than 30 publications have been published to date [4].

2.2. SPECIFIC IAEA GUIDANCE FOR COUNTRIES WITH NEWLY ESTABLISHED NUCLEAR POWER PROGRAMMES

The IAEA provides direct support to Member States in the area of nuclear infrastructure development primarily via:

— Development of guidelines [5–8];
— Assistance in performing self-assessments and performing Integrated Nuclear Infrastructure Review (INIR) missions [9];
— The IAEA technical cooperation programme;
— Regional and international workshops on infrastructure development related issues.

INIR missions are IAEA coordinated peer reviews conducted by a team of international experts upon the request of a Member State. These missions can be used to evaluate the status of a country's progress towards implementation of its nuclear power programme by utilizing the milestones approach, as presented in Ref. [5]. Nuclear power infrastructure development is split into three progressive phases. The completion of each phase is marked by a specific milestone at which the progress of the development effort can be evaluated. This allows the Member State to ensure sequentially at each milestone that it has: (a) comprehensively recognized and identified the national commitments and obligations associated with the introduction of nuclear power; (b) established and adequately prepared the entire national infrastructure required to begin the construction of a nuclear power plant; and (c) established all necessary competences and capabilities to be able to regulate and operate a nuclear power plant safely, securely and economically over its lifetime, and to be able to regulate and manage the ensuing radioactive waste.

In addition to its numerous publications providing safety and technical guidance on national nuclear power programmes, the IAEA has published key overarching strategic publications. The most recent of these with a direct impact on small and new nuclear power programmes is the 2015 revised guide on the milestone approach and issues to be considered when launching a nuclear power programme [5], the revised guide on methodology how to evaluate the progress of nuclear power infrastructure development [6], and the 2009 guide on policies and strategies for waste management [7]. The first two divide the development of necessary infrastructure for a nuclear power project into three phases: (a) planning a decision, (b) preparation for implementing the project; and (c) project implementation. Each of these stages is marked by a specific milestone, indicating readiness: (a) to make a commitment to a nuclear power programme; (b) to invite bids or negotiate contract for a first nuclear power

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Disposal of Radioactive Waste, IAEA Safety Standards Series No. SSR-5, IAEA, Vienna (2011).

plant; and (c) to commission and operate the plant. Each milestone requires an adequate level of development of relevant infrastructure: 19 issues, including issue 16 on SNF and issue 17 on RWM, are discussed. However, the requirements relating to waste management are given at what has to be planned and implemented for each phase and respective milestone: awareness and understanding of the problem and establishing basic formal infrastructure for the first milestone (presented as formulating national policy in the area); arranging practical measures to prepare for implementation of a waste management system for the second milestone (selection of waste and spent fuel management strategies); and installation of waste management facilities for the third (commissioning of all at-reactor and necessary away-from-reactor storage facilities). The specific waste related issues to be considered at each milestone are summarized in the following:

(1) Milestone 1 — Ready to make a knowledgeable commitment to a nuclear power programme. The major considerations include:
- Knowledge of the current national capabilities, regulatory framework and experience with radioactive waste handling, storage and disposal;
- Knowledge of the additional volume of low and intermediate level waste (LLW and ILW) and variety of isotopes expected from nuclear power facilities;
- Knowledge of individual steps in nuclear fuel cycle and feasible options for national fuel cycle strategy covering front end and back end;
- Potential resources of supplies and services for each step;
- Knowledge of technological options and research pursued internationally for the ultimate disposal of spent fuel and high level waste (HLW) from reprocessing;
- Options for financing spent fuel and radioactive waste management and disposal;
- The human resources and other infrastructure development needs associated with RWM for a nuclear power programme.

(2) Milestone 2 — Ready to invite bids for a first nuclear power plant. Early considerations include:
- Revising the laws and regulations associated with radioactive waste disposal;
- Developing provisions for capacity of the on-site spent fuel storage, waste volume and toxicity minimization and requirements for associated facilities as part of the bid specification;
- Planning to enhance the waste disposal programmes and facilities to be prepared to accommodate the operation of a first nuclear power plant, including provisions for on-site storage;
- Assigning responsibility to continue to follow international efforts and progress on HLW disposal;
- Establishing policies and assigning responsible organization with clear terms of reference to lead the national planning for disposal of LLW, ILW and HLW;
- Understanding the extent to which geological conditions exist in the country to allow disposal of all types of radioactive waste and/or the potential for contracting for waste disposal with other countries;
- Establishment of national strategies for spent fuel management (with respect to reprocessing, interim storage, transportation and final disposal) and for management of all expected radioactive waste streams;
- Establishing plans to fully finance long term radioactive waste management, radioactive waste disposal and decommissioning.

(3) Milestone 3 — Ready to commission and operate a first nuclear power plant. The necessary conditions at this time are:
- Existing, enhanced or new facilities for the storage or disposal of LLW and ILW are fully operational and are prepared to receive waste from the nuclear power plant;
- The responsible organizations and funding system have been established;
- The responsible organizations continue to follow international efforts and progress towards ultimate HLW disposal and revise national policy as appropriate;
- Plans for implementing the interim storage strategy for spent fuel, consistent with on-site storage capacity are developed (including identifying a suitable location, transport capabilities and funding arrangements).

The key waste related message given is as follows: radioactive waste needs to be managed in such a way as to avoid imposing an undue burden on future generations; that is, the generations that produce the waste have to seek and apply safe, practicable and environmentally acceptable solutions for its long term management. In certain circumstances, safe and efficient management of spent fuel and radioactive waste might be fostered through agreement among countries to use facilities in one of them for the benefit of the others.

In more practical terms, this can be summarized as:

- — A spent fuel and RWM infrastructure is a necessary element of the system to be available when implementing nuclear power programmes.
- — The infrastructure can be best built through formulating national spent fuel and radioactive waste policy and relevant strategies.
- — Its development and implementation requires a systematic, stepwise approach lasting for several decades.
- — Building of the waste management infrastructure should be initiated in the early stages of planning nuclear power programmes.

IAEA Nuclear Energy Series No. NW-G-1.1, Policies and Strategies for Radioactive Waste Management [7], explicitly addresses the need for a strategy and policy. The policy set out by the national government specifies a set of goals that ensure safe and efficient waste management. The implementer(s) of waste management have then to develop appropriate strategies to achieve these goals. The steps towards establishing a strategy and policy, as presented in Ref. [7], are illustrated in Fig. 1.

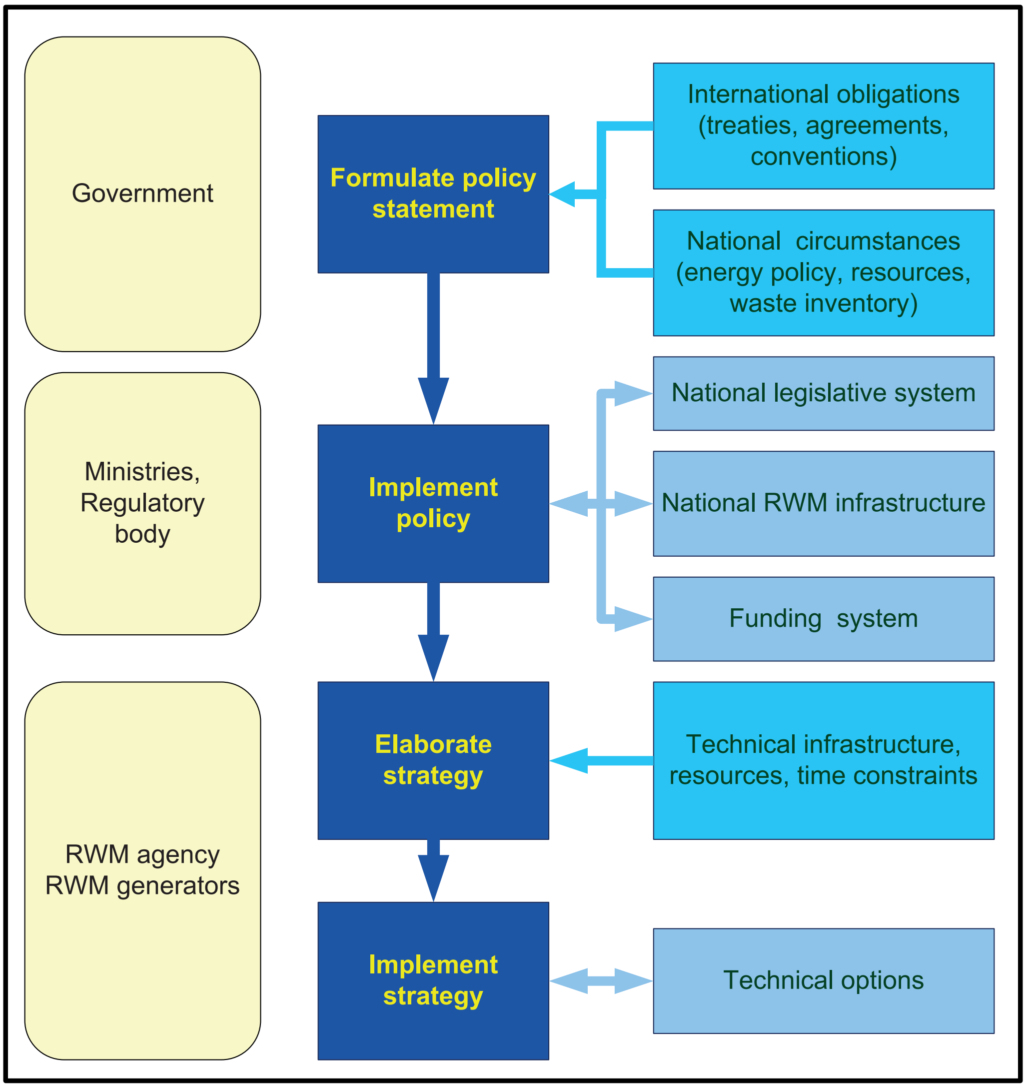

FIG. 1. Principal steps in the development and implementation of a national radioactive waste management (RWM) policy and strategies [7].

Reference [7] emphasizes that the policy in any country is to be based on the IAEA Fundamental Safety Principles [3], but that its content will depend on country specific aspects, including the types and quantities of waste arising, the financial and human resources available, and the demographics of the country. For all categories of waste, from very low level residues through to spent fuel and HLW, strategic management options are briefly presented. The importance of identifying an end point for each waste stream is stressed, even if a long period of interim storage is part of the strategy. In the context of this publication, annex I of Ref. [7] is of special interest, since it presents a typical policy for a country with a small amount of radioactive waste. It includes tables of technical options for all waste types and recommended management end points for particular waste streams, as well as elements to be considered when developing waste management strategies in countries with greatly differing scope in their nuclear activities.

At a more holistic level, the IAEA also supports Member States in their long range and strategic planning and decision making on nuclear power programmes through the application of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) methodology [10]. The INPRO methodology aids Member States in strategic planning and decision making on long term nuclear energy deployment, and it may also help newcomers to compare different nuclear energy systems in order to find the preferred one consistent with sustainable development objectives. The INPRO methodology can be applied in a nuclear energy system assessment or to build awareness, in particular, for nuclear 'newcomers'.

2.3. EUROPEAN UNION

On 19 July 2011, the Council of the European Union adopted the directive on radioactive waste and spent fuel management [11]. The directive requires[3] the following of EU Member States:

— Member States have to draw up national programmes within four years of the adoption of the directive (by 2015). National programmes are to include plans for the construction and the management of final disposal facilities and for laying down a concrete timetable for construction, with milestones and a description of all activities that are required to implement the disposal solutions, costs assessments and the financing schemes chosen.
— The ultimate responsibility for the management of radioactive waste lies with each Member State. However, two or more Member States can agree to share a final repository located in one of them. The public is to be informed by the Member States and be able to participate in the decision making on nuclear waste management.
— Safety standards drawn up by the IAEA become legally binding.
— A framework for the national radioactive waste and spent fuel management policies is to be implemented in each Member State; in particular, a legislative and regulatory infrastructure is to be established to set up a national radioactive waste and spent fuel management programme.

The directive is based on and fully respects the IAEA Fundamental Safety Principles [3] and the adopted European Commission nuclear safety directive [12] establishing a Community framework for the nuclear safety of nuclear installations; both publications are directly cited in the current directive [11].

Rising interest in the use of nuclear power in many European countries has also led the European Union to produce waste specific guidance for Member States introducing or expanding reactor programmes. The waste subgroup of the European Nuclear Safety Regulators Group (ENSREG) produced a publication [13] on waste management and decommissioning in which many of the principles of the IAEA publications are reiterated. It advocates preparation of a national programme for waste management covering the following tasks:

— Take stock of existing solutions for managing radioactive materials and waste (with particular focus on gaps in decisions, policies, methods, responsibilities, waste streams);
— Identify the foreseeable needs and establish the necessary capacity for installations;

[3] Based on http://europa.eu/rapid/press-release_MEMO-10-540_en.htm?locale=en

— In case there is no management solution for existing waste, define a programme to identify a solution and to implement it;
— Organize research into the management of radioactive materials and waste;
— Based on a principal political decision, fix, at the national level, a process for all subsequent decisions required for the implementation and follow-up of the envisaged solutions (who decides, what, when, on which bases, with which societal legitimization).

To support the implementation of the directive on radioactive waste and spent fuel management and to help European policy makers develop national programmes, the European Commission's Joint Research Centre (JRC) and the European Academies' Science Advisory Council (EASAC) published in 2014 Management of Spent Nuclear fuel and its Waste [14]. The report describes the options for spent fuel management, covering open, partially closed and fully closed nuclear fuel cycles, as well as challenges associated with different options.

The report emphasizes the importance of defining a spent fuel management policy and ensuring that the necessary technical and financial resources are available, now and in the future, for the safe and responsible management of spent fuel.

Advice to EU Member States on developing a geological repository is provided in the roadmap [15] produced by the waste subgroup of the European Nuclear Energy Forum. The aim is to provide guidance to EU Member States that are starting out or are at an early stage in the decades long process leading towards the implementation of geological repositories for high level radioactive waste or SNF, if this is deemed to be a waste. The roadmap is intended to be generic enough to be applicable to all Member States, independent of their current position; ideally, the national roadmaps to be developed will be compatible with this, but will differ in the specifics of approach and timing. An important conclusion of the report is that "Considering the long time spans involved in waste management, sustained political commitment is essential. Plans for new reactors should not be put forward without a comprehensive and credible programme for spent fuel and radioactive waste management" [15]. For countries with small or newly established nuclear power programmes, the issue of planning for disposal is of particular importance. The roadmap reaffirms that deep geological disposal is to be the end point in a national waste management programme for such waste, "Since it is the only technically feasible way for the safe long-term management of high level waste and spent fuel, if regarded as waste" [15].

In practice, there is no huge technical driver in small programmes for early implementation of geological disposal facilities. However, there are important societal reasons for advanced countries showing the way, and in all countries, political decisions have to be taken to ensure that geological disposal is implemented without undue delay [15].

2.4. OECD NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency seeks to assist its members in developing safe, sustainable and societally acceptable strategies for the management of all types of radioactive material, with particular emphasis on the management of long lived waste and spent fuel, and on decommissioning of disused nuclear facilities. Its Radioactive Waste Management Committee (RWMC), assisted by three working parties — the Forum on Stakeholder Confidence, the Integration Group for the Safety Case and the Working Party on Management of Materials from Decommissioning and Dismantling — issues technical documents and collective statements, organizes peer reviews, publishes informative leaflets and overviews, and supports international technical meetings [16].

Currently treated technical and conceptual topics in the field of disposal include optimization, dealing with very long timescales, assessing the state of the art in safety assessment methods and the operation phase of repositories.

In a 2008 collective statement [17], the RWMC suggests, inter alia, that a geological system provides a unique level and duration of protection for high level radioactive waste, and that it is safe and technically feasible based on IAEA safety standards and the recommendation of the International Commission on Radiological Protection. While a 'wait and see' strategy is hardly acceptable for its ethical and safety constraints, a number of countries have adopted geological disposal as the reference long term management solution; progress towards its implementation is evident. Its implementation is conditioned by a broadly accepted national strategy including implementation roadmaps; the development process requires decades, which allows for programme adaptation and enhancement, including application of the reversibility and retrievability concept. Siting a repository is a critical step facing political and social challenges. This can be overcome by open and transparent selection processes, flexible strategies and the involvement of stakeholders in decision making.

3. NUCLEAR POWER PLANT WASTE ARISINGS

This section provides an overview of the types and quantities of radioactive waste produced throughout those parts of the nuclear cycle that are most relevant for countries embarking on a nuclear power programme.

3.1. OVERVIEW OF CONDITIONED WASTE PRODUCED

Radioactive waste is produced throughout the nuclear fuel cycle as well as from other nuclear activities in medicine, industry and research. For establishing and operating a structured waste management scheme, it is of great practical value to classify the waste in a logical manner relating to the requirements on its handling and disposal. Various schemes have evolved for classifying radioactive waste according to the physical, chemical and radiological properties that are of relevance to particular facilities or circumstances in which radioactive waste is managed. These schemes have led to a variety of terminologies, which may differ from State to State and even between facilities in the same State. In some instances, this has given rise to difficulties in establishing consistent and coherent national waste management policies and implementing strategies; it can also make communication on waste management practices difficult nationally and internationally. The IAEA classification scheme is given in IAEA Safety Standards Series No. GSG-1, Classification of Radioactive Waste [18]. A number of elements of an earlier classification scheme were retained. However, the scheme was modified to reflect experience gained in developing, operating and assessing the safety of disposal facilities.

In para. 2.2 of GSG-1 [18], six classes of waste are derived and used as the basis for the classification scheme:

(1) Exempt waste (EW): Waste that meets the criteria for clearance, i.e. it has been cleared from regulatory control, it is not considered radioactive waste.
(2) Very short lived waste (VSLW): Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared for uncontrolled disposal, use or discharge.
(3) Very low level waste (VLLW): Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control.
(4) Low level waste (LLW): Radioactive waste with only limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities.
(5) Intermediate level waste (ILW): Waste that, because of its content, particularly of long lived radionuclides, requires disposal at greater depths, of the order of tens of metres to a few hundred metres.
(6) High level waste (HLW): Waste with levels of activity concentration high enough to generate significant quantities of heat, or waste with large amounts of long lived radionuclides. Disposal in deep, stable geological formations, usually several hundred metres or more below the surface, is the generally recognized option for disposal of HLW.

Nuclear power production gives rise to the generation of several kinds of radioactive waste, the most hazardous of which are spent fuel (if it is declared waste) and other HLW that is generated mainly from chemical reprocessing of spent fuel. In addition, VLLW, LLW and ILW are all generated as a result of reactor operations, reprocessing, decontamination, decommissioning of nuclear facilities and other activities in the nuclear fuel cycle. In the present section, the waste that arises in countries with or without nuclear power is briefly described. Section 4 then records the technical approaches that are currently used to ensure that this waste is managed safely at all times.

3.2. WASTE FROM REACTOR OPERATION

In the operation of nuclear power plants, raw waste arises from the processing of cooling water and storage pond water, from equipment decontamination and from routine facility maintenance. Waste generated from routine operations includes contaminated clothing, floor sweepings, paper and plastic. Waste from processing of primary coolant water and the off-gas system includes spent resins and filters, as well as some contaminated equipment. Waste may also be generated from the replacement of activated core components such as control rods or neutron sources. Once they have been conditioned as described below, the waste is mainly VLLW or LLW, with small quantities of ILW. The LLW makes up around 90% of the volume of all radioactive waste from nuclear power, but only around 1% of the activity. The ILW makes up some 7% of the volume and has 4% of the radioactivity of all radioactive waste.

These are most commonly conditioned by solidification in cement (bitumen or polymers are other alternatives), using regular or specially formulated grouts. The process can be used to solidify liquid waste directly (sludge, concentrates) or to encapsulate solid waste (ashes, metallic components, compacted waste, etc.). The resulting packages[4] can be easily handled and stored in conventional warehouse type buildings. The necessary shielding of the packages during handling and storage must, however, be considered. Since the included radionuclides are short lived, disposal can be in a near surface disposal facility.

The volumes produced depend on the reactor type, but a typical 1000 MW(e) pressurized water reactor (PWR) will generate about 100–200 m^3 of LLW and ILW per year. Volumes of raw waste (before processing) are much higher, which requires appropriate dimensioning of collection and storage facilities. Reduction of waste generation can preferably be achieved while designing reactors: thorough segregation of waste types and streams enhances application of clearance, delay decay and reuse/recycling principles, and combined with selection of effective treatment technologies, results in significantly decreased amounts of waste to be processed and disposed of.

While management of raw waste is an integral part of a reactor complex, processing and predisposal storage facilities need to be constructed in parallel as a separate task.

3.3. WASTE FROM DECOMMISSIONING

Although decommissioning of a new nuclear power plant will start many decades after commissioning, it is prudent to have a decommissioning strategy from the outset and to prepare estimates of the types and volumes of waste that will arise and will need to be disposed of (required for planning RWM facilities). The activities involved in decontamination and dismantling of a nuclear facility and the clean-up of the site will lead to the generation of radioactive waste that may vary greatly in type, level of activity concentration, size and volume, and may be activated or contaminated. This waste may consist of solid materials such as process equipment, construction materials, tools and soil. The largest volumes of waste from the dismantling of nuclear installations will mainly be VLLW and LLW, and can be disposed of like the operational waste. An exception involves some reactor internals with long lived radionuclides, which are ILW that should be considered for disposal in a geological disposal facility [19]. In most cases, the voluminous biological shield and all of the secondary plant are either short lived LLW or are so inactive that they are cleared as EW and can go to conventional disposal facilities. A typical 1000 MW(e) PWR or boiling water reactor produces between 5000 m^3 and 10 000 m^3 of decommissioning waste [20].

3.4. SPENT FUEL

Most reactor fuel is in the form of fuel elements comprising pellets of ceramic uranium dioxide sealed within thin metal tubes (e.g. stainless steel or zirconium alloys) that are bundled together in a fuel assembly. After it has been in the nuclear reactor, the fuel becomes intensely radioactive, largely as a result of the formation of fission products. With time, the buildup of fission products within the fuel reduces its efficiency and, after a few years, it needs to be removed from the reactor (becoming ‘spent fuel’) and replaced. At this time, the original enrichment

[4] Different types of package are used by different organizations, e.g. 200 L waste drums, 400 L concrete ‘drums’, 1 m^3 concrete boxes, ‘20 foot’ containers, etc.

of fissile ^{235}U in the fuel (3–5%) has been reduced to about 0.8% and the content of fission products and newly formed heavy elements, including plutonium isotopes, is about 5%.

After removal from the reactor, the spent fuel is stored under water for several years to allow cooling. It can thereafter be shipped for reprocessing or else transferred to longer term wet or dry storage before being encapsulated in preparation for emplacement in a geological disposal facility, if direct disposal is the chosen strategy. Spent fuel assemblies would be sealed into a metal canister for emplacement in a disposal facility. Figure 2 illustrates one example of the numerous existing designs of fuel assembly and a disposal canister.

Spent fuel remains radioactive for a very long time (see Fig. 3). It is for this reason that it must be isolated from humans in an environment that will be stable for long periods times. Deep geological formations represent the only such environment that can be accessed by humans.

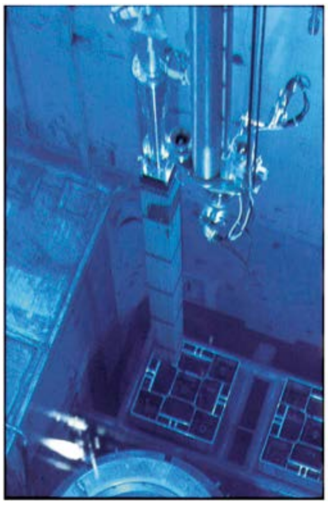

FIG. 2. Spent fuel assemblies reloaded under water from a transport container to a storage rack of an interim storage facility (left). A steel and copper disposal canister (right) contains several assemblies (courtesy of SKB, Sweden).

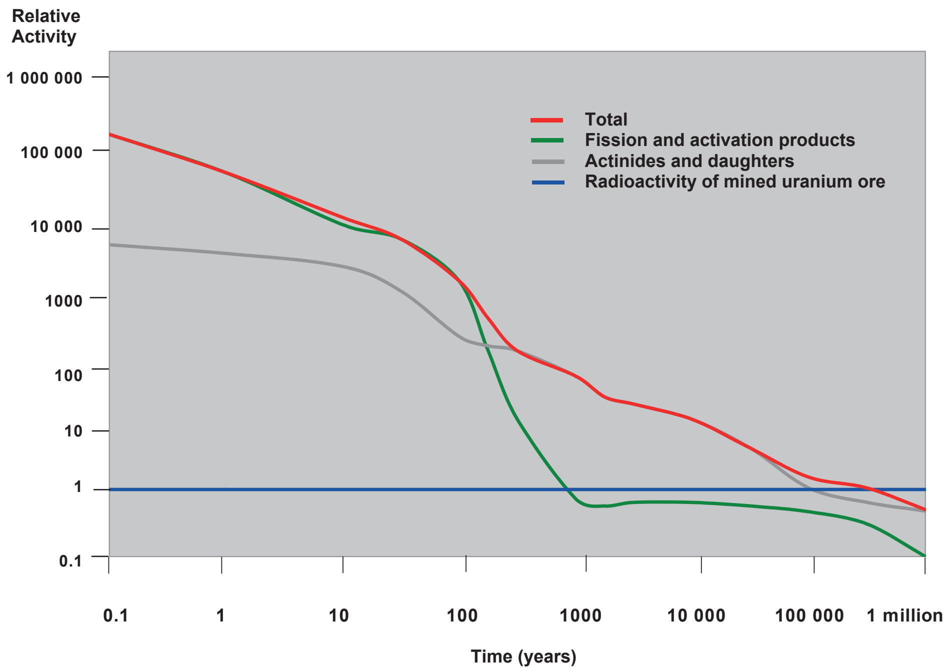

FIG. 3. Decay of activity of spent fuel relative to the activity of the uranium ore from which it was mined (the ore activity is still well above the permissible health limits).

The quantities of spent fuel that are produced by modern nuclear reactors depend upon the reactor and fuel type and other technical parameters, operational history and the fuel burnup (level of neutron irradiation of the fuel). Modern LWRs with a capacity of 1000 MW(e), an availability of 90%, an efficiency of 35% and a burnup of around 45 GW·d/tU will generate only around 25 t of spent fuel per year. Higher burnup figures (over 60 GW·d/tU) are being aimed at, and this will reduce the spent fuel quantities further. HWRs that can use natural uranium generate larger quantities of spent fuel. Per 1000 MW(e), a Canada deuterium–uranium (CANDU) reactor produces, in a year, around 125 t of spent fuel (but the specific activity and decay heat from spent fuel from a CANDU reactor is much lower than that from LWRs, which might simplify its later management).

3.5. WASTE FROM REPROCESSING AND RECYCLING

SNF contains about 2% fissile material (1% remaining ^{235}U, 1% plutonium and minority actinides) that can be isolated (reprocessed) and recycled as a new fuel (see Section 4.2.2). With current reprocessing technologies this process generates all waste categories containing all remaining radionuclides from used fuel. The HLW accounts for over 95% of the total radioactivity produced in electricity generation if a reprocessing policy is followed. It originates as a liquid residue from reprocessing spent fuel to extract the uranium and plutonium for reuse. The liquid contains most of the radioactivity from the original spent fuel. It is commonly evaporated to dryness, and the residue containing the radionuclides is then melted with a much larger volume of inert glass-forming material to produce a homogeneous, solid, vitreous waste form. The glass is cast in stainless steel containers that are sealed and may be placed in a further metal container for emplacement in the disposal facility (see Fig. 4).

In the reprocessing option, more waste streams need to be dealt with in addition to the HLW itself. These other waste streams include intermediate level structural waste such as hulls and nozzles from fuel assemblies, and intermediate level process waste, for example sludge from liquid effluent treatment. Typically, 1 t of reprocessed PWR fuel[5] generates about 0.1 m^3 of HLW, 2.5 m^3 of ILW, 1.5–3 m^3 of LLW (all values are after conditioning, including the waste package/container) and 950 kg of uranium which can be reused for new fuel production.

The most important other waste streams produced in reprocessing spent fuel is the long lived ILW composed of the hulls and endcaps of the metal tubes that contained the fuel, and other parts of the fuel elements. These can be embedded in a matrix of cement inside a steel container or can be compacted into steel cylindrical containers similar to those containing the HLW.

FIG. 4. Solid radioactive waste forms. Left: Cutaway showing simulated vitrified HLW in a stainless steel production container. The container is 1.3 m high and holds about 150 L of glass. Right: Cutaway showing simulated cement encapsulated intermediate level waste from reprocessing of spent fuel (metallic fuel cladding waste) in a 500 L stainless steel drum. Several such drums might be placed in a steel or concrete box, surrounded by an additional cement matrix, for disposal (courtesy of BNFL).

[5] See https://ukinventory.nda.gov.uk/wp-content/uploads/sites/18/2014/02/2010-UK-Radioactive-Waste-Inventory-Main-Report.pdf

Finally, each of the industrial processes involving recycling eventually produces decommissioning ILW, LLW and VLLW. Current practice is to return vitrified HLW and ILW[6] (including the equivalent of LLW) generated during reprocessing to the country of spent fuel origin; this country is responsible for selecting a suitable disposal option. ILW canisters will also require geological disposal, although they can be more closely packed than the HLW canisters since they generate little heat. The reprocessing step reduces the volume of highly radioactive waste. The total radioactivity is, of course, unchanged, but is distributed in a very different way. Over the past few years, commercial reprocessors have dramatically reduced the waste volumes that they produce, and they also retain the large volume of low level technological waste that they generate. Accordingly, countries that contract for reprocessing receive back smaller volumes. In 2004, for example, the La Hague plant in France produced 66 containers each of vitrified waste (HLW) and compacted hulls and nozzles (ILW) per hundred tonnes of spent fuel that were reprocessed; these 180 L steel containers contain about 150 L of waste [19]. The fuel assemblies comprising the 25 t of spent fuel emerging in one year from a 1000 MW(e) reactor have a volume of around 10 m^3; the fuel volume after encapsulation for disposal will be about 75 m^3. Reprocessing results in only around 2–3 m^3 of vitrified HLW; this corresponds to 14 standard waste canisters of the type shown in Fig. 5. The packaged volume for disposal would then be around 30 m^3.

3.6. OTHER WASTE

Although this publication is devoted to waste from nuclear power plants and spent fuel, it is useful to remind countries with small or newly established nuclear programmes that, even without nuclear power, there is radioactive waste to be managed in their country. In fact, a comprehensive waste management and disposal programme should take all radioactive waste in the country into consideration. A brief overview of typical non-nuclear-power waste follows.

(a) Medical waste: The use of isotopes for medical diagnosis and treatment results in the generation of mainly short lived waste. After a period of decay storage, most of the waste can be disposed of as exempt or non-radioactive waste. When radiography sources have decayed to a point where they are no longer emitting enough penetrating radiation for treatments, they are considered as radioactive waste. Sources such as ^{60}Co and ^{137}Cs are mostly treated as short lived (although they may be too active for disposal in a LLW facility), but other sources such as ^{226}Ra are long lived and may need to go to geological repositories.

(b) Industrial waste (mostly disused sealed radioactive sources (DSRSs)): Industry utilizes radioactive sources for a wide range of applications. The majority are short lived, but some, including thousands of ^{241}Am smoke detector sources compacted into steel tubes, are classified as long lived. Other industrial waste is naturally occurring radioactive material (NORM), which results from the concentration of naturally occurring radioactivity via industrial processes. This waste is often discharged or disposed of as normal industrial waste, but some NORM may require measures typical for LLW or ILW to protect the environment. Typical examples of NORM waste arise from the oil and gas industry (pipe scale), phosphate fertilizers and scrap metal, among other things.

(c) Research waste: Generally, sources utilized at research establishments are disposed of as short lived waste, but ^{226}Ra and ^{241}Am sources used in biological and agricultural research are long lived. Research reactors produce the same types of waste (spent fuel, operational, decommissioning) as commercial reactors, but on a much smaller scale. Accelerators also produce waste during their operation, and a large accelerator gives decommissioning waste volumes similar to those of nuclear power plants (but less concentrated).

(d) Waste from other nuclear fuel cycle activities: Other nuclear fuel cycle activities producing radioactive waste include uranium mining and enrichment. The latter is not likely to take place in countries embarking on a nuclear power programme, but some potential new users of nuclear power will have indigenous uranium reserves. The management of the voluminous waste produced by mining and milling is a challenging task that is not addressed here. An illustration of all fuel cycle activities producing radioactive waste is given in Fig. 5. Many of the activities are relevant only for providers of nuclear services and not for countries embarking on nuclear power.

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[6] Depending on service provider, the arrangements may vary. Sometimes only HLW (with equivalent amount of activity) is returned to the customer.

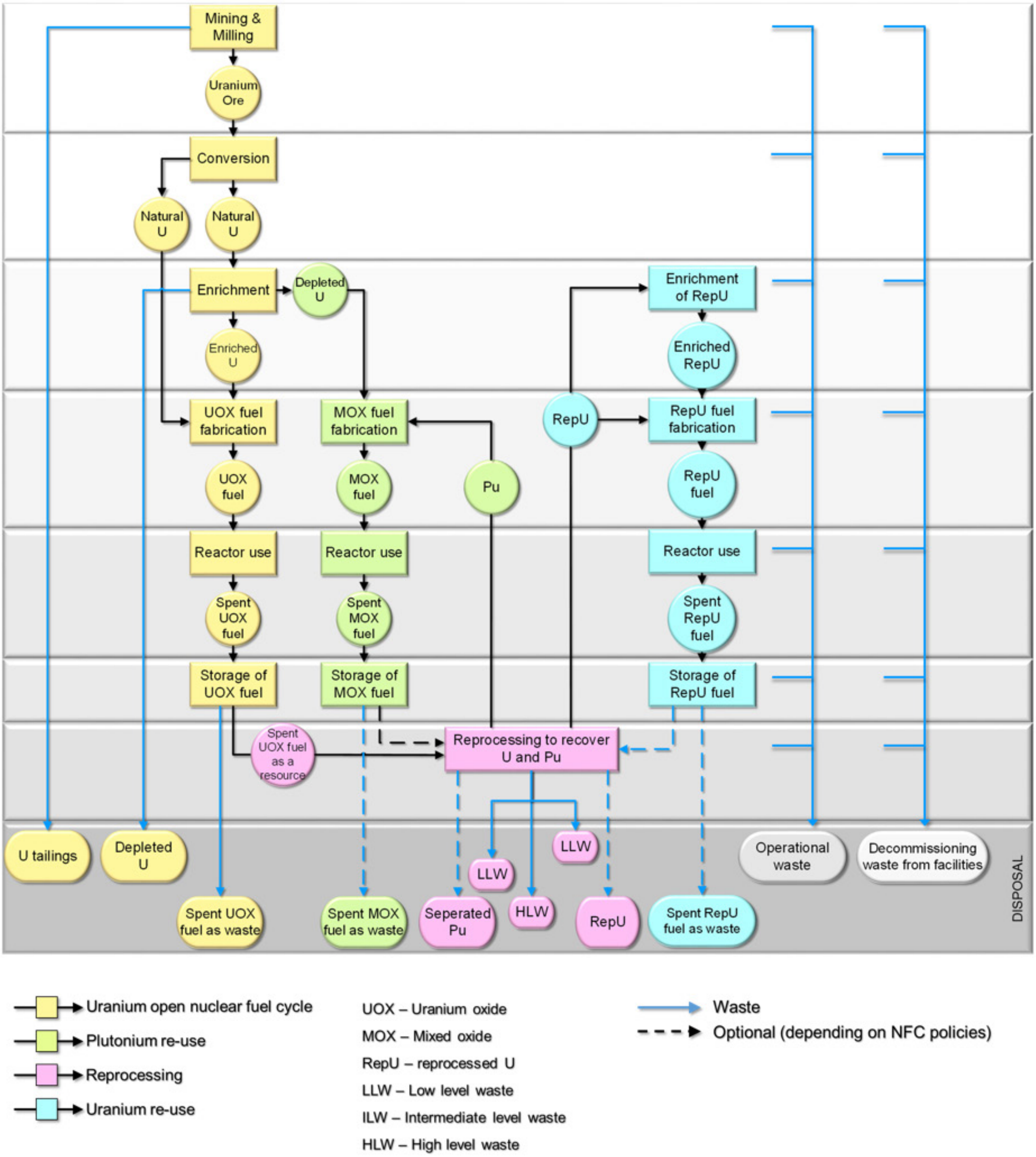

FIG. 5. An example of possible wastes and materials generated at different steps of the nuclear fuel cycle. Different colours indicate different nuclear fuel cycle options.

4. TECHNICAL OPTIONS FOR WASTE MANAGEMENT

The most efficient RWM strategy is the minimization of waste generation while exploiting nuclear and radiation facilities. Ideally, this will have already been achieved in the design stage of the facilities by selecting appropriate technologies and designs (at-source waste reduction), but also during collection of waste (segregation and consequent clearance, recycling and/or reuse) and processing of the remaining waste by employing efficient waste management technologies. This section briefly presents proven technological options with regard to these approaches.

4.1. MANAGEMENT OF VERY LOW, LOW AND INTERMEDIATE LEVEL WASTE

4.1.1. Managing waste from reactor operation

The waste that requires the most immediate attention when a country introduces nuclear power is the waste that is continually produced during reactor operation.

4.1.1.1. Processing operational waste

Some very low gaseous or liquid discharges are produced during reactor operation, but most liquid, gaseous and solid waste is retained at the plant. Most of the waste is subjected to treatment and conditioning processes that convert it into a form that is suitable for subsequent management, such as transport, storage and disposal. The principal aims of waste processing are to minimize the volume and to reduce the potential hazard of the waste by conditioning it into a stable solid form that immobilizes it and provides containment. Volume reduction can be by compaction or incineration (solid waste), and by evaporation, ion exchange and membrane processes (liquid waste); it is important to note that, in these processes, the amounts of radioactive materials remain the same. Conditioning processes such as cementation or encapsulation in bitumen or polymers are used to convert liquid waste into a stable solid form that is insoluble and will prevent dispersion to the surrounding environment. Packaging the immobilized waste is carried out in, for example, metallic drums, or metallic or concrete boxes or containers. Solid VLLW is not conditioned, but simply packed to ease its handling and transport. Facilities for processing operational waste need to be commissioned in time for startup of the reactor.

4.1.1.2. Storage of very low, low and intermediate level waste

Facilities for the storage of VLLW and conditioned LLW and ILW need to be fully operational and prepared to receive waste from the commissioned nuclear power plant. Fortunately, this task has been safely carried out for decades at many locations throughout the world. Nevertheless, careful planning, including preparation for a final waste destination (a disposal facility), good engineering and adequate financing mechanisms, are all necessary.

Storage of the LLW and ILW from reactor operation is straightforward if the technologies for solidification have been implemented so that standardized waste packages can be produced. These can be stacked and stored in conventional buildings that need not be especially strengthened. However, a good shielding and radiation protection regime (particularly for ILW) and a comprehensive data management system need to be implemented. New nuclear power programmes need to ensure that sufficient storage capacity is made available at reactor startup; adequate storage facilities should be planned to manage the lifetime operational waste arisings.

4.1.1.3. Disposal options for very low, low and intermediate level waste

Many of the facilities required for processing operational waste and for on-site storage can be provided by reactor vendors. Disposal, on the other hand, is a task that must be addressed by the operators (or entrusted institutions) themselves. Its availability needs to be harmonized with a capacity of waste storage. For the VLLW and LLW that can be disposed of in facilities at or near the surface (see Fig. 6), technical solutions have been developed and implemented in many countries, including Finland, France, Japan, Spain, Sweden and the United States. In fact, commercial services for designing and building near surface repositories are available on the open market. The stumbling block in numerous countries has, however, been the selection of a suitable and accepted site for such facilities. Public opposition to any type of radioactive waste disposal facility has delayed or prevented implementation of many near surface repositories. Countries with a newly established nuclear power programme need to be aware of this and to institute a siting programme at an early stage. Actual implementation of the LLW disposal facility can, however, be postponed for a considerable time, since the volumes of waste produced in the

FIG. 6. The Centre de l'Aube low level waste disposal facility and the very low level waste facility in Morvilliers, France (courtesy of Andra).

operation of modern power plants are so low that storage for decades is no real problem — although with an operating disposal facility, on-site stores can be smaller.

If the decision is taken to dispose of LLW and ILW from reactor operations in geological disposal facilities, this may be planned in the scope of a co-disposal facility that may also accept spent fuel or HLW. This means that disposal will take place only decades after reactors begin operating. Some countries (e.g. Germany and Switzerland) have, however, opted to dispose of all waste in deep repositories and to consider the option of dedicated geological repositories for LLW and ILW.

The costs of disposing of LLW and/or ILW in near surface facilities are much lower than those for spent fuel or HLW that must go to deep geological repositories, but they may arise at an earlier time in a developing nuclear power programme.

Because of the ease of storing waste for many years, disposal facilities are not technically required at the outset. However, the extended technical and societal efforts required to site and construct a disposal facility imply that a programme for doing this need to be initiated early.

4.1.2. Managing decommissioning waste

Today, it is increasingly expected that a decommissioning plan for a nuclear reactor is prepared by its designer and provided by a vendor before the start of operation. This necessitates producing estimates of the types and volumes of waste arising and deciding on end points for this waste. That the decommissioning task is not trivial is clear when one realizes that the total volume of waste from decommissioning and dismantling a 1000 MW(e) power station may be around 5000–10 000 m^3; the amount and activity of waste depends on the selected decommissioning strategy (immediate or deferred action). To date, several power reactors have been completely decommissioned and dismantled, with the sites released for unconditional use, several more have been partly dismantled and safely enclosed, and dismantling work is in progress at over 50 sites.

The options for decommissioning nuclear power plants range from returning the site as soon as possible to a greenfield state through to entombing the structures for a hundred years or more in order to allow substantial decay of radioactive materials. The option chosen will depend on regulatory requirements, public and political opinion, and safety and economic considerations.

The longer one waits before dismantling and disposal, the higher is the fraction of waste that can go to conventional disposal sites, or VLLW sites, rather than to LLW repositories, which have more engineered barriers and are therefore more expensive. Typically, in VLLW disposal, the waste is placed on an impermeable membrane in large trenches excavated in a clay layer. The trenches are filled with sand and then covered by plastic and a clay layer. Inspection holes are used to check that there is no water seepage around the waste. VLLW disposal facilities designed to accept voluminous rubble from decommissioning activities have been implemented in, for example, France and Spain. In both these cases, this has been carried out close to operating LLW repositories at, respectively, Centre de l'Aube and El Cabril.

4.2. SPENT FUEL MANAGEMENT

The IAEA Fundamental Safety Principles [3] raise, in Principle 7, para. 3.29, the ethical requirement that "Radioactive waste must be managed in such a way as to avoid imposing an undue burden on future generations". However, management of spent fuel may require activities to be performed for more than a century, no matter whether the fuel is disposed of directly or reprocessed (open and closed cycles, respectively). Thus, the generations that produce the fuel will need to provide adequate assurance and resources — organizational, technical, economical, legal and safety — to enable their successors to eventually render the fuel harmless.

In contrast to the activities involved in the management of LLW, not all of the steps for cradle to grave management of highly radioactive spent fuel have, as yet, been implemented in practice. There are different strategic options for managing spent fuel, and these options require different technologies. The basic options for managing spent fuel are illustrated in Fig. 7.

An attractive option for those countries with newly established nuclear power programmes could be to arrange take back of the used fuel by its supplier (sometimes called fuel leasing). The availability and scope of this scheme is subjected to case by case assessment: conditions for such services have been negotiated between the Russian Federation and some countries (Islamic Republic of Iran, Turkey).

Another option is to regard the spent fuel as waste that can be directly disposed of in a geological disposal facility. Because of the initial high heat emission of the fuel, this can be effectively carried out only after a certain cooling period, which can extend to several decades (depending upon the layout and the host rock). Thus, this

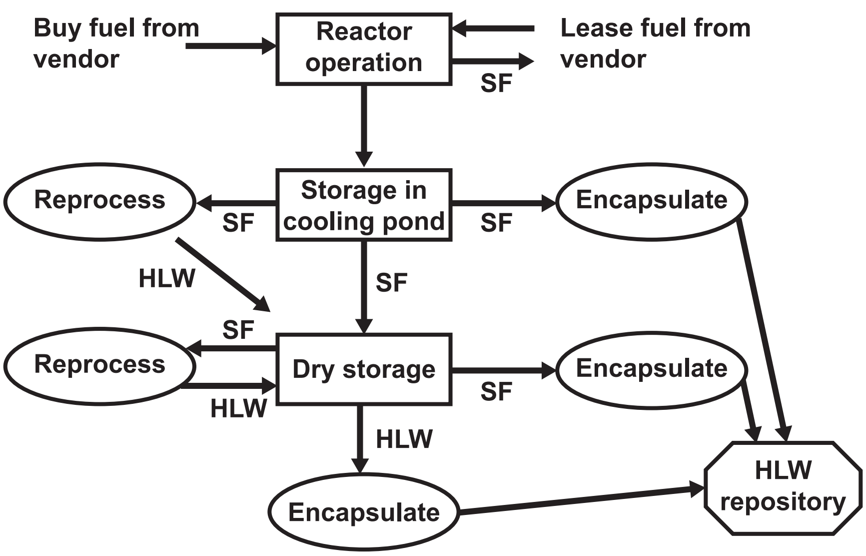

FIG. 7. Strategic options for managing spent fuel (SF) and high level waste (HLW).

strategic option requires storage facilities from the outset, an encapsulation plant before disposal and a state of the art disposal facility.

The other major option is to send the spent fuel to a reprocessing plant in which the unused uranium and the plutonium that has been created in the reactor are extracted for recycling into fresh fuel. This option remains open to countries with new nuclear power programmes for a long time into the future, since the storage facilities will be able to keep spent fuel safely for decades. The decision to reprocess or not may therefore be taken at a later stage; however, the duration of the postponement should clearly be specified with respect to the long term performance of spent fuel. On these timescales, developments of the reprocessing technologies may include the transmutation of long lived radionuclides extracted from the spent fuel into shorter lived products that can be disposed of more easily. This approach is being explored in some countries, but will not be a practicable management strategy for many decades into the future.

Reprocessing of spent fuel cannot be repeated indefinitely due to the rising concentration of radionuclides that absorb neutrons (so called neutron poisons), decreasing the efficiency of the fission reaction; these poisons cannot be effectively separated. Thus, PWR spent fuel can only be reprocessed twice for optimal performance and spent mixed oxide (MOX) fuel only once. This may change when advanced fuel cycles capable of burning neutron poisons using, for example, accelerator driven transmutation, are available commercially, which is not anticipated in this century. In any event, the reprocessing and reuse of fissile materials in reactor systems will result in generation of waste or spent fuel that will require final disposal in a geological disposal facility.

Finally, spent fuel from LWRs can be further exploited, after mechanical and thermal processing, in HWRs designed for natural uranium fuel (e.g. CANDU reactors) [21]. This technology has reached a full scale testing stage in China.

4.2.1. Storage of spent fuel

All water cooled reactors store the SNF, when it is unloaded from the reactor, under water in a pool on the reactor site. Originally, it was planned that spent fuel would be shipped off-site after a few years of cooling; the fuel would then go for reprocessing or for longer term storage to allow further cooling before direct disposal. In practice, reprocessing is currently carried out in only a few programmes, and disposal of spent fuel has not yet taken place. The need for storage has thus increased, and most countries have implemented interim away-from-reactor storage.

The cooling time before spent fuel can be disposed of in a geological disposal facility depends upon the design and geology of the disposal facility and on the characteristics of the SNF. Typically, it is in the range of 30–50 years or even longer. Besides these technical reasons, some countries may have other constraints, which may impact their disposal schedules. For countries with small nuclear power programmes, many years of operation would be required to accumulate an inventory of spent fuel that justifies embarking on their own deep disposal facility project. Table 1 gives an overview of the storage technologies available today [22].

Following the years of storage in pools at the reactor sites, spent fuel is increasingly being stored in dry storage facilities, which have lower operational costs and can be implemented in a modular fashion. The casks can be purchased as required; they do not require a strengthened or strongly shielded building and can even be placed on pads in the open air. There are also concepts for multipurpose casks that can be used for transport, storage and perhaps even disposal of spent fuel. If large quantities of spent fuel (above about 600 t) are ready for extended storage at one time, dry storage in a vault also becomes an economical solution.

Most storage facilities are built above ground, although there are exceptions such as the Swedish Clab spent fuel pool, situated in a rock cavern some tens of metres below the surface, and underground dry storage solution in the United States (at Callaway and San Onofre sites).

There are no major technical issues affecting the safety and security of away-from-reactor spent fuel storage. Both wet and dry storage systems have been proven over decades (see Fig. 8). However, there are some specific challenges to be considered. A pool at the reactor storage that collects fresh fuel with high thermal output calls for increased passive safety measures to ensure sufficient cooling, even in highly improbable beyond design basis situations. In addition, pool storage requires that a large facility must be constructed at the outset to allow for future accumulation of spent fuel, so that much of the storage space remains unused for a long period. Moreover, maintenance can become expensive if disposal lies far into the future. For dry storage, there are some concerns

TABLE 1. STORAGE OPTIONS FOR AWAY-FROM-REACTOR STORAGE OF SPENT FUEL [22]

Type	Option	Heat transfer	Containment (medium)	Shielding	Feature	Examples
Wet	Pool	Water	Water/building	Water	Classic option	Most at-reactor storage, many away-from-reactor storage
Dry	Metal cask	Conduction through cask wall	Double lid metal gasket (inert gas)	Metallic wall	Dual purpose	CASTOR, TN, NAC-ST/STC, BGN
	Concrete cask/silo	Air convection around canister	Cavity lining/seal welding (inert gas)	Concrete and steel over pack	Vertical	CONSTOR, HI-STORM
	Concrete module	Air convection around canister	Canister sealing (inert gas)	Concrete wall	Horizontal	NUHOMS, NAC-MPC/UMS, MAGNASTOR
	Vault	Air convection around thimble tube	Thimble tube	Concrete wall	Several cases	MVDS, MACSTOR
	Drywell/ tunnel	Heat conduction through earth	Canister (inert gas)	Earth	Below ground	Not commercial

Note: Dual purpose casks can be used for transport and storage of spent fuel.

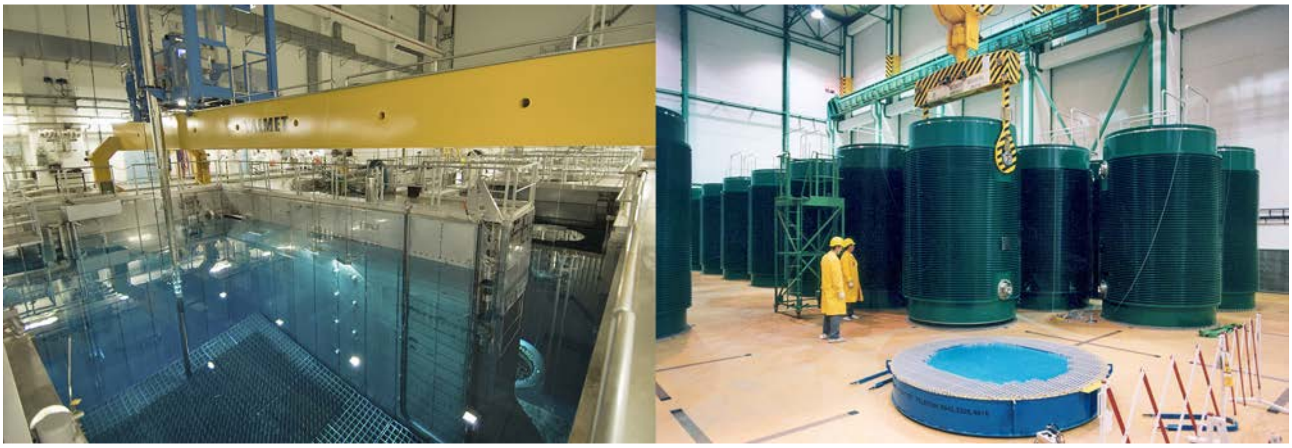

FIG. 8. Examples of wet and dry storage facilities (Olkiluoto NPP wet storage and Dukovany NPP dry storage).

about the long term integrity of the fuel, and it will require a follow-up programme to ensure that the fuel can be removed from the containers after many years.

Security concerns have heightened interest in the potential advantages of building storage facilities underground, possibly with the alternative of later converting these stores into disposal facilities. This concept has been referred to as a ‘hardened’ facility (UK Committee on Radioactive Waste Management). Some storage facilities have also been assessed against commercial aircraft and missile impacts. Globally, the quantities of spent fuel in storage will continue to grow over the coming decades for the following reasons:

— The first deep geological repositories in Sweden, Finland or France will begin operation in the early 2020s, with other countries planning their commissioning around the mid century or even later.
— Repositories in other countries will be much later because of institutional delays, because sufficient inventories need first be accumulated or because funding is not yet available or new nuclear reactors are planned to be put in operation in the future.

— Revived interest in reprocessing followed by burning isolated fissile materials in new reactor systems may lead some countries to extend surface storage in order to keep the option open or to be able to profit if spent fuel becomes, at some future date, an asset rather than a liability.

Typical casks can contain 12–18 t of LWR fuel. This implies that each year, a large power reactor produces spent fuel that would fill one or two casks. The costs of spent fuel storage have been reviewed in the Support Action: Pilot Initiative for European Regional Repositories (SAPIERR) project [23], primarily for dry cask facilities since this is the most commonly chosen approach for the future. There are very few recent data on the costs of existing systems; the most recent information is available from Ref. [24].

4.2.2. Spent fuel reprocessing and recycling in thermal reactors

In current reprocessing facilities, the used fuel is separated into its three components: uranium, plutonium, and waste containing fission and activation products (see Section 3.6). The uranium from reprocessing can be reused as fuel after conversion and enrichment, if necessary. The plutonium can be made into MOX fuel, in which uranium and plutonium oxides are combined. The vitrified waste is a high quality standardized product that is well suited for geological disposal. Parts of the technological waste are of much lower activity and can go to near surface disposal sites.

Plutonium quality in storage degrades with time as a result of ^{241}Pu decay and the buildup of ^{241}Am. MOX fuel is currently more expensive than fresh UO_2 fuel; the specific decay heat is around twice that of spent UO_2 fuel; the neutron dose from spent MOX is about 80 times that of UO_2 fuel. Reprocessed uranium is a ‘free’ by-product, but with modern high burnup levels, there is less residual ^{235}U and more ^{236}U. Moreover, re-enrichment increases ^{232}U levels, and this presents a greater radiation hazard during fuel manufacturing. Re-enriching the recycled uranium produces a similar amount of tails to enriching fresh, natural uranium (the feed enrichment is higher, but the required enrichment for the product is also slightly higher), but the activity level of the tails may be somewhat higher because of the altered isotopic composition of the reprocessed uranium. In addition, when the recycled fuel is irradiated, it becomes less suitable for recycling in thermal reactors than the original spent fuel. The vitrified waste has a smaller volume than packaged spent fuel, but generates more heat per unit volume in the initial decades. It still requires disposal in a geological disposal facility, and the costs of a deep disposal facility do not decrease in proportion to the volume of the inventory. The process generates significant volumes of lower activity secondary waste. The part of the secondary technological waste that contains long lived radionuclides and must therefore go to geological disposal might need special consideration, since the waste form (cement, bitumen, compacted pieces) is less durable than vitrified waste or spent fuel.

The strongest argument in favour of reprocessing is that it conserves uranium resources, although the real benefits will be realized only when fast reactors are in use (practically all depleted uranium could be converted into fissile materials). A further positive aspect is that the highly active glass, in contrast to spent fuel, does not fall under IAEA safeguards and presents no proliferation risk. However, the fact that current reprocessing technology involves separation of weapons usable plutonium has led to concerns about the spread of the technology to many countries.

On the other hand, a decision on reprocessing should be based on careful consideration of technical, economic as well as infrastructure needs to support such a decision [25]. Finally, spent MOX fuel also has to be adequately managed (currently, it is not reprocessed). The economic considerations could, however, change with the introduction of fast reactors. While it is evident that the once through open fuel cycle is currently the dominant option, “the combination of reprocessing followed by recycling in today’s reactors should be seen as an interim phase of nuclear power development, pending widespread use of fast neutron reactors” [26].

Figure 7 indicates that HLW and sometimes ILW from commercial reprocessors are returned to the customer countries. This is the situation today, although early reprocessing contracts with France and the United Kingdom had no return of waste. Public and political opposition in the reprocessing countries has led to the stoppage of this practice at the present time. In some cases, the Russian Federation can still offer a take back service for spent fuel labelled currently as ‘reprocessing and storage’.

Today, the countries that are reprocessing their spent fuel either in their own facilities or under contracts with foreign providers of such services include France, Japan (both with MOX fuel recycling), India, Italy, the Netherlands, the Russian Federation and the United Kingdom. In the past, other countries also sent fuel abroad for reprocessing, including Belgium, Germany, Switzerland (all with MOX fuel recycling) and Spain.

4.2.3. Spent fuel reprocessing and recycling in fast reactors

As pointed out above, storage of spent fuel is an established technology, uranium is relatively plentiful, and reprocessing may be challenging for small or new nuclear programmes. On the other hand, the present resurgence of interest in the use of nuclear power is leading more people to think again about the conservation of uranium resources and hence about the much higher utilization that can be achieved by recycling the fissile materials remaining in spent fuel. Fast breeder reactors (FBRs) can extend uranium resources by a factor of 100.

FBRs can utilize uranium at least 60 times more efficiently than a normal reactor, as they allow processing of all depleted uranium. FBRs can also burn most actinides, including those contained in spent MOX fuel. A new generation of fast reactors can also be fuelled by MOX. Therefore, the introduction of FBRs requires a lot of plutonium or high enriched uranium.

When fast reactors are introduced, the demand for plutonium and the ability to use recycled uranium will both increase. For these reasons, there are obvious attractions for nuclear power programmes in implementing a strategy of long term storage of spent fuel.

However, an open-ended storage policy may evoke political opposition as well as public opposition at storage sites. In addition, the costs of implementing and maintaining state of the art storage facilities needs to be considered. Estimates of the timescales on which fast reactors might be deployed in substantial numbers have varied over the years, but it is not expected that fleets of fast reactors will be deployed for 50 years or more. Proper funding arrangements and appropriate institutional frameworks must be ensured if the strategy of holding spent fuel for (far) future reprocessing is followed.

4.2.4. Direct disposal as waste

An alternative approach is to minimize long term obligations by permanently disposing spent fuel as soon as practical. Today, it is widely accepted in the technical community that the only currently feasible method to ensure very long term safety for HLW or SNF is isolation in a stable, deep geological disposal facility. Geological disposal facilities for long lived waste — if properly sited and constructed — provide passive isolation of radioactive materials. Emplacement in carefully engineered structures buried deep within suitable rock formations is chosen principally for the immense long term stability that the geological environment provides. At depths of several hundreds of metres, in a tectonically stable location, processes that could disrupt the disposal facility are so slow that the deep rock and groundwater system will remain practically unchanged over hundreds of thousands or even millions of years. Although the concept is broadly accepted, operation of geological repositories for spent fuel or HLW has not yet begun at any location in the world. However, good progress is being made in Finland, France and Sweden; several other countries have active development programmes, but no finally selected site as yet. There are technical, societal and economic challenges to be addressed in a disposal programme, and these all need to be well understood by countries with small or newly established nuclear power programmes. Accordingly, the key aspects of a disposal facility programme are identified below.

The safety of repositories for radioactive waste is based on the multibarrier concept, whereby both engineered and natural barriers within the disposal system act in concert to contain the waste (see Fig. 9). The engineered barriers proposed in advanced programmes are high technology products that contribute significantly to the overall costs of a geological disposal facility. The proposed containers are corrosion resistant for very long periods of time because they are to be made from passive materials such as copper (e.g. in Finland and Sweden) or high quality corrosion resistant alloys (e.g. in Canada or the United States), or are of massive steel construction (e.g. in Japan and Switzerland). The high costs will arise only many years into the future, since encapsulation will take place immediately before disposal. By then, it may be possible to reduce costs by using a provider of encapsulation services or by sharing encapsulation facilities with other programmes.

Suitable geological environments for deep disposal occur throughout the world. Since they can provide the different desirable features mentioned above in different combinations and to different extents, they can vary considerably in their nature. For example, national disposal programmes are considering a wide spectrum of host rock types, in which it would be feasible to construct and operate repositories at depths of several hundred metres. National choices are dependent, to some extent, on the local availability of rock formations. These include bedded and dome salt, plastic clay, claystone, mudstone, shale, marl, granite and gneiss.

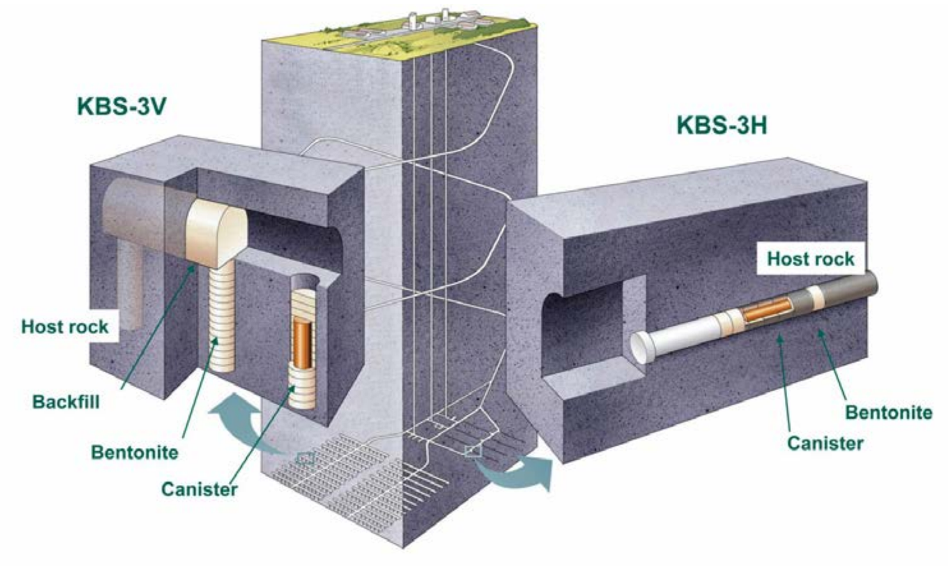

FIG. 9. The disposal facility proposed for disposal of spent fuel in copper sheathed cast iron–steel canisters in a bentonite buffer. The disposal facility would be located at about 500 m in depth in hard metamorphic or granitic rocks. This approach will be used in Finland and Sweden (courtesy of POSIVA, Finland).

It is important for countries with small or newly established nuclear power programmes to realize that once a decision is taken to implement a geological disposal facility, a decades long, multistage process begins. This involves surface exploration and scientifically based assessment of the results in order to select a suitable site; construction of access and underground exploration tunnels or shafts; construction of the disposal facility; emplacement of waste and near field engineered barriers; backfilling and sealing of sections of disposal tunnels and access ways' and finally establishment of post-closure controls.

Some important points for all countries with nuclear power programmes that are working towards geological disposal, and particularly for those with small or newly established programmes, are as follows:

- At each stage, communication and interaction with all relevant stakeholders is essential.
- Some of the stages last for years or even decades; reasons for the long periods of time are technical, operational or societal, and often for a mixture of these.
- The actual spent fuel emplacement stage cannot begin until cooled fuel is available, i.e. around 30–50 years after removal from the reactor.
- Although preparation of a comprehensive strategic plan for disposal does not require large resources, large costs arise from the first siting step onwards. Very variable construction and operation costs have been estimated by the advanced programmes, but even for small inventories, these costs are measured in billions of dollars.

4.3. MANAGEMENT OF WASTE FROM REPROCESSING

4.3.1. Storage

If countries embarking on nuclear power decide to reprocess, the waste that they will have to manage is the returned vitrified HLW and conditioned ILW (compacted or cemented hulls and endcaps). Thus, they will not have to be concerned with the processing technology itself or with the LLW streams that are produced at the reprocessors. Storage of vitrified HLW from reprocessing is similar to storage of spent fuel, but with reduced volumes. Dry storage can be in casks that are almost identical to spent fuel casks. As pointed out above, a large nuclear power plant produces spent fuel that would fill one to two casks each year. The vitrified HLW can be stored in air cooled vaults, as is carried out at the reprocessors and which has also been implemented in customer countries. The ILWs returned from commercial reprocessors today is packaged into cylinders that match the HLW canisters so that their storage is even easier, given that they have negligible heat production.

For those countries with small or newly established nuclear power programmes considering the reprocessing option, shipment of spent fuel to a reprocessing plant removes the need to provide storage space for fuel or HLW for several tens of years, since the fuel or HLW will normally be stored at the foreign plant for such long periods. In the past, this has been a significant driver for countries to buy reprocessing services. Of course, sending fuel abroad for reprocessing also involves additional transport. The plutonium that is separated in reprocessing plants poses greater storage problems. It is a highly sensitive material from a proliferation and security standpoint. It deteriorates with time and becomes less suitable for remanufacture into MOX fuel. Normally, the plutonium is made into MOX fuel for early reuse. Today, the reprocessors store the plutonium of customers (at a cost), or else use it to make MOX fuel.

4.3.2. Disposal options

Disposal of HLW from reprocessing in a geological disposal facility differs in only a few ways from disposal of spent fuel. The reduction in volume is an advantage, although full advantage cannot be taken of this since the packing density in a disposal facility is also strongly influenced by the heat emission at disposal. The absence of actinides in the HLW will lower the radiotoxicity relative to spent fuel (especially if advanced treatments based on transmutation become practicable). The heat emission at long periods of time (hundreds of years and more) is less problematic. The container design for HLW can be somewhat simpler.

The disposal benefits of HLW relative to spent fuel are, to some extent, counterbalanced by the fact that the ILW produced in reprocessing can pose new problems. This is because the ILW contains small quantities of long lived and mobile radionuclides such as ^{129}I, and these may give the earliest releases from a disposal facility.

The ILW from reprocessing can be disposed of in a separated section of a geological disposal facility for HLW or in a dedicated facility, which also must be at depth. The LLW from reprocessing does not pose significant disposal problems. This waste normally will not be returned from the reprocessor, who will dispose of it along with other larger volumes of LLW from nuclear activities.

5. AN INTEGRATED APPROACH TO SPENT FUEL AND RADIOACTIVE WASTE MANAGEMENT

The previous section looked individually at managing the various waste streams produced in nuclear power production. The practical management steps and the times at which these steps must be initiated vary between waste streams. However, it is advisable to develop from the outset an integrated approach to managing all waste that will arise, and this overarching aspect is discussed in the following subsections.

Each nuclear technology generates radioactive waste. Introduction of advanced reactor systems will result in generating new waste types and streams; some have not yet been recognized, and thus, may become a technical and safety challenge requiring adequate research and development. Even innovative waste and spent fuel processing techniques may lead to unknown (up to now) types of secondary waste. Thus, any decision on the deployment or alteration of nuclear technologies must be accompanied by thorough assessment of all technical, safety and political consequences, in particular, when regarding management of arising by-products.

5.1. THE NEED FOR AN INTEGRATED SPENT FUEL AND WASTE MANAGEMENT STRATEGY AND PROGRAMME

In the early days of nuclear power, waste management was approached in a pragmatic, ad hoc manner with attention focused on ensuring the safety and controlling the costs of operations involving waste handling and treatment. Less attention was paid to the longer term issues relating to the ultimate disposal of the waste. This was understandable, given that all of the waste volumes arising were modest, the highly radioactive waste or spent fuel required decades of cooled storage, the LLW could often be disposed of in relatively simple near surface facilities and storage capacity for all waste was easy to arrange. Today, however, it is recognized that developing, from the outset, an integrated strategy for introducing nuclear power can, in the future, avoid technical problems, reduce economic problems and enhance societal acceptance. Countries with small or newly established nuclear power programmes can learn from the experience of countries with older, mature programmes — not, by slavishly copying, but rather by thoughtful adaptation to the different boundary conditions.

The starting point is to develop a radioactive waste and SNF management policy and, based on this, a reference scenario for the future nuclear power programme (or, more often, a range of conceivable scenarios) and to estimate the waste types and volumes arising over time. Next, the technical waste management strategies to be considered need to be identified and their repercussions examined, including infrastructural, human and financial requirements. Specific potential strategies are discussed in this publication with regard to IAEA guidelines [7]. The choices will be determined by the scope of nuclear activities foreseen for the future, the scale of the power programme, the relative merits of technology imports versus buildup of autonomous expertise, etc. A prudent strategy implies arriving at a suitable balance between keeping options open and establishing a sufficiently concrete planning base.

The timescale on which all actions must be taken is a crucial issue for new programmes. Most urgent is the buildup of adequate RWM infrastructure including an appropriate legislative and regulatory environment and the relevant necessary knowledge base [7]. Another aspect to be addressed early is the financial structure set up to ensure that sufficient funding will be available for the necessary 'cradle to grave' safe management of nuclear materials including waste, as the incomes from power production are generated long before the larger part of the costs for waste and spent fuel management occur [5]. Various countries in the past have neglected this point by not diverting from the start an adequate flow of funding to ensure not only safe operational waste management but also to build up reserves for further down the line when costly storage and disposal facilities will be required.

By the time the first nuclear power plant comes on-line, a country needs to have a core body of waste management experts who can ensure that no critical issues are neglected. This body may be very small, especially if full use is made of external expertise and established networks, but core competence is essential; local experts need to be able to formulate requirements on waste systems and technologies delivered by contractors. While waste collection is an automatic part of the reactor complex, facilities for treatment, conditioning and storage of the waste need to be ordered separately, either from a reactor vendor or from another provider [5].

The following figures illustrate the importance of back end costs in the fuel cycle. Nuclear fuel costs consist of front end and back end costs. The front end costs (three quarters of the total fuel cost) are the cost of raw uranium (25%), and its conversion (5%), enrichment (30%) and fabrication into fuel assemblies (15%). The back end costs (about a quarter of the total fuel cost) include storage and direct disposal or reprocessing followed by recycling of the fissile material for reuse [27]. The cost of direct disposal is in the range of €0.5–1 million per tonne of uranium, depending on the total amount of SNF to be disposed of and on the specifics of the disposal programme [28]. These costs are only a small percentage of the total electricity generating cost (in different programmes, they are estimated at 5–8% [29]). It should be noted, however, that this breakdown will depend on the current prices of all commodities required and activities to be performed, and that some of the activities (in particular, disposal of spent fuel or radioactive waste) remain highly uncertain.

5.2. A CREDIBLE SPENT FUEL AND WASTE MANAGEMENT STRATEGY

Thus far, this publication has concentrated on the technical options available for managing specific waste streams from nuclear power production. The technologies, however, have to be applied within a credible overall management strategy, and there are also a range of possible choices for this strategy. A credible waste management strategy needs to include all waste types and to cover all phases between waste production and ultimate disposal. The most immediate issues concern implementing facilities for handling, processing and storage, and planning measures for disposal of the LLW and ILW that will start to be produced as soon as the reactor commences operation. These are tasks that have been tackled in the hundreds of nuclear power plants worldwide for decades. Therefore, the challenges for countries with new nuclear power programmes are centred on ensuring that the expertise, the technologies, the facilities and the human and financial resources required are all available at the outset.

A much more problematic and controversial part of the waste management planning concerns the establishment of a credible programme and timescale leading to the implementation of disposal facilities. Disposal facilities for LLW and ILW exist in some countries, but currently there are no such repositories in operation for the disposal of spent fuel or HLW, and this has led to much criticism from opponents of nuclear power. Accordingly, international organizations, such as the IAEA, and the European Commission have been encouraging rapid progress towards this goal, and some of the advanced programmes (e.g. in Finland, France and Sweden) are striving to achieve it in the next 10–15 years. It will be beneficial to nuclear power programmes in all countries when these advanced projects begin disposal and thereby illustrate directly their feasibility. For countries with small or new nuclear power programmes, however, it is unfeasible, or at least impractical, and also unnecessary to implement geological disposal on anything like these timescales. It will be many decades before the volumes of spent fuel or HLW from the first reactors are sufficiently large and the heat emission sufficiently low to allow disposal. Nevertheless, the public and politicians in countries embarking on nuclear power will expect to see a credible disposal strategy; pointing to the few deep repositories that may exist somewhere else in the world may not be sufficiently convincing for them.

A country with a new nuclear power programme can go further towards establishing a credible disposal strategy by taking the following steps, which are expanded upon in the IAEA publications referenced:

— Develop (probably in cooperation with foreign service providers) a sound engineering concept for disposal of the types and quantities of waste expected to arise [7].
— Define a practicable storage strategy, ensuring that safety and security are guaranteed for all accumulated waste through to the disposal step, even if this is many decades into the future [22].
— Initiate an adequate programme to study the availability of potentially suitable disposal facility sites. This can be a national programme or a dual track approach in which the possibility of sharing a disposal facility with other national programmes is also considered [30].
— Establish a funding mechanism by which the necessary financial resources are set aside, most usefully in a segregated fund, to cover all future costs [31]. The funding set aside should be continually monitored against periodically updated estimated costs to allow for any necessary adjustments.
— Ensure that the necessary core competence in waste management is built up and then maintained at the national level. This can be carried out most efficiently by creating an appropriate organizational structure with an independent waste agency whose members are offered training and education opportunities and subsequently fully integrated into the appropriate regional and global networks and independent regulatory bodies [5].

Relevant safety requirements and guides for implementation of a radioactive waste and spent fuel management system can be found in IAEA safety standards developed for all particular phases of the waste–spent fuel life cycle [32].

5.3. NATIONAL VERSUS MULTINATIONAL SOLUTIONS

As mentioned, key decisions concern the level of fuel cycle autonomy aimed at in small or new nuclear programmes. National solutions may be preferred by a country if they reduce dependence of foreign suppliers or help build a new advanced technology base in the country. Multinational solutions may be preferred by a country if economies of scale lead to lower costs, if technical or societal siting problems are reduced, or if insufficient national capacity for nuclear activities exists; however, this will not excuse the country from primary responsibility for managing its waste and spent fuel. For those back end technologies such as reprocessing or long term spent fuel storage that bring with them increased risks of nuclear proliferation of terrorist activities, multinational solutions are increasingly being advocated by the international community [33–35].

Technically and economically, the potential benefits of multinational facilities are broadly recognized, but their implementation depends on political decisions of involved countries. It should be noted that, except for SNF reprocessing, such political involvement has not yet manifested. The IAEA and European Commission have expressed a readiness to support countries that consider joint solutions for the final disposal of nuclear waste. However, the IAEA and European Commission cannot take a direct lead in any such initiatives; negotiations have to be initiated among those countries themselves. The current situation concerning multinational back end solutions is summarized below.

5.3.1. Spent fuel storage

There have been proposals that large nuclear countries could store spent fuel from countries that are short of storage space. These have not progressed, however, since the acceptance of spent fuel with no firm commitment on its return has been regarded as waste import that is not welcomed at present by any country. Multinational storage of spent fuel could, in principle, be attractive for countries with small or new nuclear power programmes, since this could ease the problems of maintaining safety and security at national spent fuel stores over long periods of time. However, by ensuring that new reactors have a pool storage capacity for decades – or even for the whole reactor lifetime – new nuclear power programmes can postpone this issue for many years.

5.3.2. Reprocessing and recycling

National reprocessing is certainly not economical for small programmes and will therefore be a goal only for those with overarching political or strategic objectives. Reprocessing and recycling by a foreign service provider is, however, an option. This service is currently offered by France, the Russian Federation and the United Kingdom[7]. For small programmes, if the economics is acceptable, the possible incentives today are to be able to move spent fuel off-site or to receive back HLW that is a quality assured vitrified form and is smaller in volume than the spent fuel.

5.3.3. Disposal

Multilateral options that remove the need for implementation of a deep geological disposal facility in each country could be much more economical than implementing a set of small national ones. They are also potentially of particular value for countries with small or new nuclear power programmes. The existence of a large, multinational disposal facility could mean that their spent fuel or HLW could go to disposal at a much earlier date than would otherwise be possible. One approach that has been proposed is fuel leasing, where the supplier retains ownership of the fuel and accepts it back into its country after the fuel is removed from the customer country reactors. Another option is that a single country or a multinational grouping provides a commercial disposal service. Fuel leasing has been offered only on a very limited scale (by the Russian Federation), and no other commercial services for acceptance of foreign spent fuel have been established.

Over the past ten years, however, there has been increasing interest in the concept of multinational or regional disposal. Support has been given by the European Commission, which has financed the SAPIERR studies devoted to this topic [23]. These studies have led to the establishment of a multinational group exploring options for a European Repository Development Organization (ERDO) [36]. The issue of import of radioactive waste remains very sensitive, however, and several countries currently have laws that forbid this and that would have to be amended before any country could volunteer to host a multinational disposal facility. The EU directive on radioactive waste and spent fuel management [11] allows that EU Member States may join a disposal facility, but limits export of EU radioactive waste beyond its borders.

The viability of multinational repository is being explored also in South Australia. The Nuclear Fuel Cycle Royal Commission, established by the Government of South Australia in 2015 to undertake an independent and comprehensive investigation into the potential for increasing South Australia’s participation in the nuclear fuel cycle, delivered its final report to the Government of South Australia in May 2016 [37]. The Royal Commission delivered 12 key recommendations, including identifying an economic opportunity in the establishment of a deep geological disposal facility and the receipt of SNF from prospective international clients. After public consultations the Citizen’s Jury rejected the proposal of the multinational repository in South Australia but the proposal is not entirely closed. The Government of South Australia maintains the option to continue public debate and have a state wide referendum on this proposal.

Every country needs access to SNF disposal, whether it has opted for direct spent fuel disposal or reprocessing, and has selected a national or multinational approach. Since disposal is the only element of current fuel cycles that

[7] The United Kingdom has taken a policy decision to cease reprocessings.

has not yet been demonstrated and implemented, every country can benefit from IAEA support. The IAEA gives high priority to these issues, as they often have high public visibility and are seen as creating potential risks and unsolved problems. There is much good research, development and demonstration experience, and good practices gathered over 30 years of systematic work. This has created a good knowledge base and increased understanding of complex features, events and processes relating to disposal. There are many good practices that should be organized and disseminated more systematically and effectively.

The IAEA provides support in a balanced and strategically productive and correct manner. This implies the following:

— The Joint Convention [1], IAEA Fundamental Safety Principles [3], IAEA safety standards and IAEA Nuclear Energy Series publications (as well as the EU waste management directive [11]) all emphasize national responsibility, and the IAEA makes clear that there is no way to release any participant from its national responsibilities.
— The IAEA can assist progress on spent fuel and HLW disposal by giving visible reinforcement to progress in national programmes. It can disseminate the knowledge that already exists through publications, training, networks and databases. The IAEA can actively encourage and support regional (and broader) cooperation in research and development relating to all aspects of developing disposal solutions at national and regional scales.
— The IAEA also recognizes that the Joint Convention [1] notes "that, in certain circumstances, safe and efficient management of spent fuel and radioactive waste might be fostered through agreements among Contracting Parties to use facilities in one of them for the benefit of the other Parties, particularly where waste originates from joint projects".
— IAEA activities are sensitive to the risk that initiatives on possible regional waste repositories may undercut both the essential priority given to national efforts (e.g. successfully starting up Finnish, French and Swedish repositories) and the Joint Convention's main message that radioactive waste should, as far as is compatible with the safety of the management of such material, be disposed of in the State in which it was generated. The concept of regional repositories should never be an excuse for a country to do nothing in the expectation that others will dispose of its waste. Nor should it slow progress in national efforts by weakening public acceptance.
— There will be expanded need for spent fuel and HLW management and disposal in view of the expected expansion of nuclear power, both because of expansion in countries with existing nuclear power programmes and because of newcomers. The IAEA is ready to support countries and other organizations in their responsible efforts to find joint solutions for the final disposal of nuclear waste.

5.4. POSSIBLE FUTURE DEVELOPMENTS THAT CAN AFFECT SPENT FUEL AND WASTE MANAGEMENT

The safe management of radioactive waste from nuclear power production is a task that will extend for a hundred years or more. It is therefore worthwhile to consider whether future developments in science or technology might lead to significant changes in the way in which the task is carried out. Current preferences of different countries include open (once through) and closed approaches, as well as prolonged storage (for many decades) of SNF.

Introduction of new reactor technologies will result in the generation of new waste streams and relevant innovative waste processing technologies that differ markedly from those used today. At the LLW end, plasma oven incineration can result in LLW that is bound into a glassy matrix suitable for LLW disposal facilities.

Large scale introduction of fast reactors may mean that only exotic spent fuels (not suitable for reprocessing) will be disposed of directly, with all standard fuels being reprocessed to extract the fissile materials. On the other hand, development of fuels that allow hugely increased burnup in the reactor may lead to decreased interest in reprocessing if the residual fissile material is greatly reduced. Partitioning of fissile waste streams from reprocessing can lead to better characterized products, with long lived radionuclides being confined to fewer waste types. Transmutation can, in principle, transform the longest lived radionuclides into isotopes with half-lives that are short enough to drastically reduce the containment requirements on geological repositories. Practical application, however, will be far in the future, if ever.

Furthermore, the growing realization that nuclear power is a necessary component of a clean and sustainable energy supply is also affecting public and political attitudes, and this may alter the institutional framework of national or multinational waste management programmes, including efforts to develop global fuel leasing and spent fuel take back systems for newcomers.

For countries with small or new nuclear power programmes, it is important to keep such potential developments in mind and, as far as is possible, to retain sufficient flexibility in their planning to allow advantage to be taken of any positive developments. However, direct reliance on technologies not yet mature enough for deployment is not a prudent approach. Elaborated waste management strategies need to be based on proven and tested approaches if they are to be credible. Some conceivable future developments are noted below.

5.4.1. Storage technologies and strategies

The safety, security and costs associated with storing spent fuel for decades or even a hundred years may all be improved if dry storage in casks becomes more common and less expensive. Storing the spent fuel underground may also be an option that accomplishes these objectives, for example, using caverns such as those of the Swedish Clab facility. Given the increasing recognition that spent fuel might be a valuable resource the probability that used fuel will be stored for many decades is rising. If this happens, then the arguments in favour of underground stores with enhanced safety and security grow stronger.

Multilateral storage options could become a more realistic option if nuclear power continues to expand. In particular, if fast reactors are developed so that spent fuel comes to be clearly viewed as a valuable resource rather than a waste, there might be less political and public opposition to a country agreeing to store foreign spent fuel.

Nuclear power programmes introducing fast reactors may be prepared to accept this resource up front to ensure the supply of reprocessable materials for plutonium extraction. The incentive for countries with small nuclear national programmes to develop multinational storage facilities is not high, since there are few economies of scale and since at-reactor storage can be maintained for a long time.

5.4.2. Advanced reprocessing

The recent support for nuclear expansion has led to the proposal, initiated by the United States [38] for expansion of reprocessing using the current technological approaches that were developed originally for extraction of plutonium for weapons. The scientific community, however, led by the National Academies, has argued that this is unnecessary and uneconomical at the present time, and that it could lead to increased rather than decreased proliferation risks. Nevertheless, the ultimate need to recycle fissile materials was accepted, and the conclusion drawn was that research into advanced reprocessing technologies was the most appropriate strategy today. If advanced technologies that are developed make reprocessing more secure, cheaper and with greatly improved waste streams, the options for countries with small nuclear power programmes may expand, especially if the increased value of plutonium fuels and the decreased hazardous lifetimes of reprocessing waste lead the supplier countries to accept spent fuel from countries with small nuclear power programmes with no return of residues.

5.4.3. Disposal

If experience with the first generation spent fuel or HLW repositories leads to cost effective, standardized technologies that make small repositories economical, and if the societal acceptance problems drastically abate owing to the positive example shown by the leading disposal countries, the implementation of many small repositories across the globe may become a less daunting prospect than it currently is. If this is not the case, then the likelihood of multinational disposal may rise. This may occur because some large programmes for commercial or security reasons begin to accept foreign spent fuel for disposal or because the above mentioned partnering efforts of small countries lead on to practical disposal projects. However, even if these options are ultimately available, they will not be fully adequate unless the waste accepting country is also prepared to take in other long lived waste generated during operation and decommissioning of nuclear reactors that needs to go to geological repositories, since this extended service is required if countries with small nuclear power programmes are to avoid the need for a national geological disposal facility.

Both the options for small countries disposing of their spent fuel abroad may become more likely in the future. As stated above, spent fuel may be viewed as a resource for advanced reactors, and thus large programmes may become more ready to enter into leasing or fuel take back arrangements. The more promising development, however, may be that countries with small or new nuclear power programmes collaborate with similarly positioned countries in efforts to implement shared, multinational repositories. It is universally accepted (and anchored in the Joint Convention) that each country has responsibility for its own waste, but this does not a priori exclude responsible transfer agreements between willing countries, if safety is assured. Cooperation among geographically contiguous or close States to develop shared regional disposal facility projects may be the most credible approach. The public and political acceptance of shared multinational or regional disposal facility concepts has increased somewhat over recent years, although opposition is still apparent in many countries, and no implementation project has yet emerged. The SAPIERR projects and the ERDO Working Group could be model examples for regional groupings elsewhere in the world.

Despite these potential positive developments with multinational repositories, the only assured way forward for new nuclear countries is to accept that a national disposal facility may be required and to work towards the implementation of such a facility, even if the possible implementation date lies far in the future. This national planning needs to make the most effective use possible of the standardization efforts being made in countries with advanced nuclear power programmes and of the opportunities for technology transfer from such countries.

6. POLITICAL, LEGAL, SOCIETAL, ECONOMIC AND TECHNICAL CHALLENGES

The technical and strategic issues covered in the previous sections provide the background required to assess the potential benefits and the challenges associated with any chosen waste management strategy. This is illustrated in this section with a range of possible strategies that reflect national choices to be made concerning the use of an open or closed fuel cycle and concerning the degree of independence that any new nuclear country might aspire to in its fuel cycle strategy.

6.1. POSSIBLE STRATEGIES FOR MANAGING THE SPENT FUEL, HIGH LEVEL WASTE AND OPERATIONAL WASTE OF SMALL AND NEW NUCLEAR POWER PROGRAMMES

The potential spent fuel waste management options for countries with small or newly established nuclear power programmes are presented here. Advantages and disadvantages as well as risks associated with these options are discussed. The list of strategic options (which may not be exhaustive) is considered under the following headings:

A: National storage and disposal (early or late) of spent fuel;
B: Spent fuel reprocessing abroad, recycling nationally or abroad and waste disposal nationally;
C: Reprocessing, recycling and waste disposal of spent fuel abroad;
D: Spent fuel national storage then disposal in a shared disposal facility;
E: Fuel leasing (similar to strategic option C);
F: Retention of spent fuel as a valuable commodity.

In principle, national and multinational storage and disposal strategies could also be considered for operational and decommissioning waste. This option is also commented upon later, but is of less interest for reasons discussed below.

This section contains an assessment of the key issues connected to the different options and how these might influence a choice of waste management strategy. The text is based on the more extensive table in Annex I.

The headings under which the topic is addressed are chosen to reflect the concerns of all stakeholders, including implementers, regulators, politicians and the public:

- Safety: This is the overriding aspect that needs to be a top priority for all stakeholders. The whole thrust of the Joint Convention is to ensure that spent fuel and radioactive waste is managed in a way that protects humans and the environment. The implementer has to be able to demonstrate that the strategy chosen ensures safety at all future times; the regulator needs to ensure that this has been carried out; and the public and its political leadership must have confidence that the experts have fulfilled their responsibilities.
- Security and non-proliferation: This is a less important issue for waste management strategies than for fuel cycle steps such as enrichment or reprocessing, but there is increasing global concern about nuclear proliferation and nuclear security so that this issue needs to be considered. Strategies that move hazardous materials into secure storage or disposal facilities as soon as feasible are preferred over approaches that leave such materials at many surface locations for long periods of time.
- Economics: This is a significant aspect for the implementer assessed through a cost–benefit analysis, and optimized use of national resources should be a goal for any country. Moreover, the policy and regulatory requirements need to ensure that sufficient funding will be available for all activities, including those that will first be performed relatively far in the future. Because of the long timescales involved, strategies that delay expenditures until dates far in the future will tend to be preferred if only economic issues are examined and if normal cost discounting rule are applied.
- Political: In waste management, the feasibility or practicability of implementing any national strategy is strongly affected by overarching political considerations. This has been amply illustrated by national programmes that have been abruptly halted because of a governmental policy decision (e.g. the Yucca mountain project in 2009, United States), or by a public referendum (e.g. the Wellenberg project in 1995, Switzerland) or because of advice given by governmentally appointed commissions (e.g. by the Canadian Seaborne Panel in 1998). The issue of multinational nuclear cooperation, including potential transfers of waste between countries, is particularly sensitive for politicians.
- Legal: Clearly, there must be a clear policy and strategy supported by a sound legal framework, or else one has to be established. Currently, several countries have legislation that would rule out some of the strategic options A to F described above.
- Societal: Experience in many countries has shown that a sufficient degree of societal support must be achieved before any waste management strategy can proceed in an orderly fashion. Public views on the safety of waste management and particularly on the siting of waste storage and disposal facilities will directly affect the practical feasibility of any waste management strategy. This implies that any successful strategy must successfully tackle the challenge of communicating openly with all the involved stakeholders.

In addition to these aspects, it is important that any country choosing a waste management strategy carefully considers the infrastructure requirements and human resources required. A small country may not be able, on its own, to assemble the critical mass of scientific experts that are required to plan and implement a safe and secure approach. This problem may be mitigated by engaging in intensive cooperation with IAEA networks, a larger supplier of nuclear services or by coordination with other small countries in the same position.

6.2. ANALYSES OF POSSIBLE SPENT FUEL AND WASTE MANAGEMENT STRATEGIES

6.2.1. Management of spent fuel

In Annex I, the relevance of each of the above six evaluation criteria to each of the potential back end strategies (A–F) is noted in tabular form. The following summary assessments of each strategy are based on the points recorded in the table in Annex I.

A: National storage and disposal (early or late) of spent fuel

Today, national storage and disposal of all radioactive waste, including spent fuel if it is so defined, is the basic strategy for almost all countries with a nuclear power programme. Reasons for selecting direct disposal of spent fuel may vary and have been chosen, for example, by countries with small programmes, countries that had planned only a limited duration of their nuclear power programme, countries that had proliferation concerns associated with reprocessing (e.g. the United States) or countries that simply found the current costs of reprocessing to be unacceptably high (e.g. Switzerland). All of the technical activities necessary can be carried out safely and securely. The costs are high in absolute terms, but still represent only a relatively small fraction of nuclear power production costs. Disposal is possible only after some decades, and postponing this step to even later dates may allow funds to accumulate or may allow for further technology developments. In principle, any country running or starting up a nuclear power programme needs to have a baseline strategy that involves all waste management operations being carried out at a national level. This may be carried out in a 'dual track' approach in which multinational options are also kept open, but it is not prudent to rely from the outset on the emergence of multinational options. This principle, and its impact of possible life cycle costs, needs to be borne in mind by any country contemplating the introduction of nuclear power.

B: Spent fuel reprocessing abroad, recycling nationally or abroad and waste disposal nationally

The possibility of having reprocessing carried out abroad is a first step towards multilateral cooperation on the back end of the fuel cycle. Today, this is an available strategy choice for any country with a nuclear power programme, since there is a commercial market providing reprocessing services. For a country with a small or new nuclear power programme, there are potential benefits as well as drawbacks to this strategy. The benefits include: early removal of spent fuel from the reactor site; postponement of the building of interim storage facilities, since the HLW will not be returned for several years; lower storage and disposal volumes for HLW than for spent fuel; and reduced proliferation concerns, since fissile materials need not be returned from the reprocessor. The disadvantages start with costs: today, recycled fuel is more expensive than fresh fuel. A further significant drawback is that the ILW, which is also returned to the country (see also Section 3.5), increases the volume for disposal and can present greater long term safety concerns than the vitrified HLW, which is a high quality product that can be packaged in very long lived containers. Several countries (e.g. Germany, Spain and Switzerland) that chose this strategy have, in the meantime, ceased reprocessing their spent fuel. This was not only for cost reasons, but also because there was significant public and political opposition to reprocessing. Storage of materials recovered by a foreign reprocessor is not viable (plutonium decay products decrease its quality and there is limited use of reprocessed uranium); these can either be sold or used for the country's reactors as MOX fuel. In the latter case, management of spent MOX fuel needs to be included in the overall spent fuel management strategy, and reactors must be adapted to burning MOX fuel. It is conceivable that the introduction of fast reactors will lead to greater incentives for having fuel reprocessed.

C: Reprocessing, recycling and waste disposal of spent fuel abroad

If a foreign reprocessor were able to provide a disposal service to countries with small nuclear power programmes, or else to arrange disposal in a willing third party country, this would certainly be an attractive proposition. Of course, the price would have to be acceptable. The price that the small country would be willing to pay is obviously influenced by the savings that it could make by avoiding the need for its own geological disposal facility. However, nuclear countries also produce small quantities of other long lived waste, and an end point for this waste is also required so that the disposal service provided abroad may have to include more than just the HLW and ILW from reprocessing. Although a few countries currently have policies or laws that exclude disposal abroad, political and public acceptance of such strategies is unlikely to be a problem, provided that all parties are convinced that the safety measures at the foreign disposal facilities be state of the art.

D: Spent fuel national storage then disposal in a shared disposal facility

From the point of view of a country with a small or a newly established nuclear power programme, this strategy has much in common with the previous one. Since it has little use for recycled plutonium or uranium, it is of little consequence for a country with a small programme whether the fuel that is shipped abroad is reprocessed or simply disposed of. The economic benefits to the small country can be more easily achieved if the shared disposal facility is based on a partnering approach in which all expect to benefit from the economies of scale involved. The politics of disposal are somewhat different if reprocessing is not part of the strategy. Disposal of foreign waste in a large country that has benefited commercially from reprocessing foreign fuel may be a less sensitive issue than shipping of foreign fuel to a foreign country purely for disposal. However, if the disposal facility is in a country that belongs to a group of partnering countries and that has volunteered to take on this role, then political and public acceptance will be less of a problem. The challenge, of course, is to build a partner group, which includes one or more countries that are ready to host the shared facility.

E: Fuel leasing

This is, in practical terms, very similar to option C, since the country with a small nuclear power programme can simply export its spent fuel when it emerges from the reactor. An important difference, however, is that this option may be politically and legally easier, since the fuel can be deemed never to have changed its owner. From the point of view of the lessor, the disadvantage of having to accept back the fuel is balanced by the added commercial fuel supply opportunities afforded and by the possibility to reuse the fissile material. The lessee may well be willing to accept higher fuels costs as well as reduced freedom of choice in fuel supply in return for the disposal benefits (although the earlier condition concerning the need for disposal of other long lived waste applies here also). The international non-proliferation community has strongly favoured fuel leasing approaches, since a much tighter control of fissile materials results.

Fuel leasing services have been negotiated between the Russian Federation and some newcomer countries (Islamic Republic of Iran, Turkey). Russian law[8] has provisions that allow repatriation of SNF of Russian origin for reprocessing and after storage period returning back HLW on a commercial bases. If embarking countries are negotiating such arrangements with fuel supplier, it is important to clarify whether disposal of HLW and ILW is included or not. If yes, the contracts should be sufficiently binding to give confidence in disposal arrangements and should preferably include costs of these arrangements, as this might be an important element for assessing the viability of the nuclear power programme [5].

F: Retention of spent fuel as a valuable commodity

This is a strategy that may become more favoured by countries with nuclear power programmes, both large and small, if the future of nuclear fission continues to look more positive and will include with time the large scale introduction of fast reactors. Recent developments in several countries indicate that their national strategy may move in this direction. The upsides are clear: spent fuel can be relatively easily stored for long periods of time; expensive disposal facility projects are postponed; and the spent fuel may become an asset as reprocessing costs decline and uranium costs increase. The downsides are largely relating to the public and political perceptions of nuclear power. Since indefinite storage is not a realistic option, this strategy can be interpreted as a demonstration that there is no final solution for the waste from nuclear power production. Accordingly, if this strategy is adopted, then it needs to be backed up by a credible strategy that indicates how (and even better where) the disposal steps can be implemented with current technologies. At a practical level, it should also be noted that ensuring safe, very long term storage of spent fuel is still dependent on some further technical studies (fuel ageing and corrosion), as well as on provision of resources for maintaining and refurbishing the storage facilities.

6.2.2. Management of operational waste

As mentioned earlier, national and multinational options can also, in principle, be considered for storage and disposal of operational waste. However, the national approach is basically accepted by all countries with nuclear power programmes. The technical and financial requirements are lower than for storage and disposal of spent fuel or HLW. For countries with small or new nuclear power programmes, the critical point is that facilities for managing

[8] Decree of the Government of the Russian Federation No. 418 from 11 July 2003 on import of spent fuel assemblies from power reactors to the Russian Federation.

operational waste are required at a much earlier time, as is made clear in the IAEA milestones approach [5]. The siting of disposal facilities for operational waste can also be challenging: the technical requirements may be easier to meet, but achieving societal acceptance, especially by the host community, can become a problem. Accordingly, countries embarking on nuclear power programmes would be well advised to have on hand at the outset a credible and transparent siting strategy and not to unduly postpone its implementation. A potential difficulty could be the disposal of ILW that is not acceptable to near surface. This could mean that, even if spent fuel and HLW can be managed multinationally, two repositories still need to be built (surface and subsurface) or that all LLW has also to go to a subsurface disposal facility.

Nevertheless, there are not large incentives for multilateral disposal of operational waste. The technical and economic challenges of safe management can be addressed even by countries with small programmes, the economies of scale are not large and the volumes are such that transport could become a problem. However, it is not totally inconceivable that contiguous countries might share disposal facilities for operational waste. For example, in the United States, a few LLW sites serve all of the states. However, the United States also illustrates, through the continuing struggle to block imports of Italian LLW, that the political hurdles to acceptance of foreign waste are not confined to spent fuel or HLW.

7. CONCLUSIONS

After some remarks on the general challenges facing countries embarking on a nuclear power programme, this section summarizes the steps to be taken when a non-nuclear country transitions into a nuclear power producer. It then reviews the waste management challenges that face a country introducing nuclear power and finally looks briefly at how the global nuclear community might assist and at what the aspiring nuclear country needs to undertake.

7.1. PLANNING FOR RADIOACTIVE WASTE MANAGEMENT IS ESSENTIAL FOR INTRODUCING NUCLEAR POWER

It is a major policy decision involving long term political, technical, financial and societal commitments when any country chooses to undertake a new nuclear power programme. Nevertheless, a large number of countries have contacted the IAEA in recent years to seek guidance on taking such a decision. The IAEA has responded by providing guidance and safety standards, arranging workshops and training events, conducting peer reviews, and distributing and sharing information through various networks, databases and meetings. Radioactive waste will be produced only after the reactor is commissioned, and the first waste that arises during operation is of low activity and modest volumes, and can be easily stored at the plant. The spent fuel that begins to accumulate is even lower in volume, and will, in all cases, require storage for some years in the cooling ponds that are part of the reactor complex. In the past, during the first era of nuclear expansion in the 1960s and 1970s, this apparent lack of an urgent need for comprehensive waste management plans extending through to disposal led many countries to underestimate the importance of the issue. In particular, the public and political pressure that would be placed on identifying solutions to waste management problems was underestimated, as was the time expected to elapse before final repositories became available.

The situation was eventually realized by the nuclear community, and progress was made in national programmes for storage and disposal of radioactive waste, although still more slowly than hoped for. The IAEA has published extensive guidance on how and when waste management programmes are to proceed; the European Commission has incorporated this in the obligatory directive. The guidance given to countries with large and long established nuclear power programmes is, however, not always directly transferable to those with small or new nuclear power programmes. This is particularly clear when implementation schedules are discussed. Countries with long established nuclear power programmes will have accumulated sufficient waste inventories to technically and economically justify implementation of repositories, and they should have accumulated sufficient funding to finance these. On the other hand, countries with new nuclear power programmes will have no need for a geological disposal facility until the first spent fuel is cool enough for disposal, i.e. in 40 or more years. Guidance for countries with new or small nuclear power programmes needs to take these differences into account.

7.2. TRANSITION FROM A NON-NUCLEAR TO A NUCLEAR POWER PROGRAMME

Typically, any country deciding to initiate a nuclear power programme will have limited experience in the management of radioactive waste. Often, however, there will already be small amounts of institutional waste (mostly medical) and DSRSs, so that radiation protection practices are known. In some cases, there may also be NORM from the mining industry (uranium, oil, gas, phosphates). In this case, there may also be experience with managing large quantities of low active material. Often, the management of institutional waste and DSRS will be in the hands of a research institute. Sometimes, there is no nuclear regulatory body and certainly no funding sources other than direct government financing. One of the biggest challenges will be the lack of trained personnel in all of the technological areas associated with the use of nuclear power.

The transformation process that needs to take place for a smooth introduction of nuclear power requires detailed and intensive planning. The recommended approach described in the IAEA milestones approach [5] is a step by step procedure that lasts for a considerable time. The infrastructure requirements relating to establishing regulatory and implementing bodies, developing approved RWM policies and strategies, and establishing funding systems based on the 'polluter pays' principle are adequately covered in this advisory publication.

More explicit guidance can be given to the generator of spent fuel and radioactive waste. A number of technical activities are to be readied immediately, including:

— At-reactor liquid waste cleaning systems;
— Storage of raw waste (LLW and ILW, solid and liquid);
— Processing of raw waste (LLW and ILW, solid and liquid);
— Storage of conditioned waste (LLW and ILW);
— Transport/handling means for LLW and ILW;
— At-reactor SNF storage.

In addition, consideration has to be given to possible future requirements for away-from-reactor SNF storage, potential storage of reprocessing HLW and ILW, and transport/handling means for HLW and SNF. Disposal facilities for all types of radioactive waste must be planned, with the implementation of those for short lived waste being the most urgent. Countries with large, established nuclear power programmes often have or plan for separate disposal facilities for VLLW, LLW, ILW, SNF and/or HLW. Countries with new nuclear power programmes need to consider which of these facilities will be required at which future times.

Of equal importance with the technical activities associated with starting a nuclear power programme — and with dealing with the long term waste management issues that arise through such a decision — are the societal challenges to be tackled. These obviously include technical and scientific education and training schemes. In many countries, however, ensuring constructive interaction with the public and with potential host communities for waste management facilities will be a crucial element in the transition to a nuclear country.

7.3. KEY MESSAGES FOR COUNTRIES WITH SMALL OR NEW NUCLEAR POWER PROGRAMMES

The strategic advice given by international bodies such as the IAEA and principles raised in the EU directive [11] are applicable to almost all countries with a nuclear power programme. To act on the overarching guidance, however, more detailed planning is required. This detailed planning is not identical for countries with large and small nuclear power programmes. A graded approach, taking into account the differences in scale and timing, is required. In this publication, the boundary conditions determining the strategic approach for new nuclear countries have been expanded upon, and the particular options for long term management examined. From this, it is possible to distil a set of key messages for countries with small nuclear power programmes. These are as follows:

(a) A responsible nuclear power programme needs to consider the life cycle of all facilities and all materials from the outset (What facilities will be needed? At which times? What are the end points for all materials?). Solving a partial problem does not necessarily bring benefits if not assessed within the entire management system context.
(b) Countries with small or new nuclear power programmes need an integrated policy and strategy for all proposed nuclear activities; this needs to include the management options for all types of radioactive waste and spent fuel.
(c) Even if disposal is far off, planning and organization need to begin at the initiation of the programme; this can help with technical and economic optimization and (importantly) also with public and political acceptance.
(d) Resources (human and financial) must be made available for planning and implementing the policy and strategy. This also includes long term aspects. Even if disposal of HLW or spent fuel lies far ahead, the programme needs to allocate the responsibility for being informed about options ('intelligent buyer').
(e) The IAEA has given, in its technical publications and safety standards, high level guidance on policy, strategy and milestones to countries with new nuclear power programmes; this publication addresses more specifically and with more practical solutions the issues faced by countries with small or newly established nuclear power programmes.
(f) Important strategic lessons can be learned from countries with advanced nuclear power programmes, but these have to be adapted to allow for the different boundary conditions of new and small programmes [39]. The key differences relate to:
    (i) Size of the programme (i.e. inventory);
    (ii) Scope of nuclear activities (level of self-sufficiency aimed at);
    (iii) Timescales involved;
    (iv) Resources available (human, financial and technical).
(g) A 'wait and see' policy — if this implies that no actions are being taken or planning being initiated — is not an option. There are minimum steps that any country with a nuclear power programme needs to initiate, even if only one or a few reactors are foreseen. Of course, this does not imply that a final waste management strategy is to be fixed at the outset; the planning can include a range of options that are to be kept open.
(h) At a minimum, a country with a new nuclear power programme needs to, in the context of the national policy and relevant strategies for managing radioactive waste and SNF:
    (i) Allocate responsibilities;
    (ii) Create adequate infrastructure;
    (iii) Organize funding mechanisms;
    (iv) Mobilize national resources, in particular, educate and train personnel;
    (v) Agree on strategic approaches and develop reference options (plan facilities, timescales, etc.);
    (vi) Consider all siting issues for all facilities, including assessing co-siting possibilities;
    (vii) Start consideration of the feasibility of national disposal facility siting options;
    (viii) Engage in international networks.
(i) The most urgent tasks include:
    (i) Establishing an expertise base;
    (ii) Allocating responsibilities for particular elements of waste and spent fuel management;
    (iii) Ensuring that all at-reactor facilities required for safe collection, handling, treatment and conditioning of operational waste and for storage of SNF will be available from day one;
    (iv) Ensuring sufficient storage capacity for raw and conditioned waste and SNF will be available at all future times;
    (v) Establishing credible disposal options and planning for initiating their commissioning in due time with respect to availability of storage capacities.
(j) The management of institutional waste, including DSRS, needs to be considered as part of the integrated strategy.
(k) There is a range of worldwide proven options open to countries with new nuclear power programmes. Their selection depends on local conditions and preferences, in particular on:
    (i) The national legislative system;
    (ii) The allocation of responsibilities for planning, execution and funding;
    (iii) The timing chosen for storage and disposal (e.g. prolonged storage);

(iv) The storage and disposal technologies chosen (e.g. wet or dry storage for spent fuel, shallow or deep disposal for conditioned waste);
(v) The fuel cycle options (reprocessing or direct disposal, advanced fuels, etc.);
(vi) The degree of self-sufficiency (indigenous or imported fuel cycle and waste management services, national or shared regional storage and disposal, security of supply of services, etc.).

It is not necessary to choose definitive solutions at the outset; options can be kept open, provided timing for an eventual decision is fixed, but a minimum level of engagement is required for all open options.

One can identify valuable existing examples of national programmes (for more information, see Annex II) that illustrate specific points, for example:

— Slovenia: The country, with one reactor, has organized storage for all fuel produced during its lifetime, developed a long term plan leading to national disposal while also keeping multinational options open (dual track), and organized funding [40].
— Netherlands: A formal decision was taken to postpone disposal for 100 years in order to build up a sufficient HLW inventory for a national disposal facility and to accumulate sufficient funding. Studies for the development of a national deep geological repository have been initiated, but multinational options are also being kept open [41].
— Belgium, Hungary and Switzerland: These exemplify countries with relatively small nuclear power programmes that are pressing ahead with structured national projects for disposal of LLW and HLW [42, 43].
— Finland: This is a good example of how a country with a small nuclear power programme can progress with a national disposal facility project, given good geological environments, intelligent technical and societal approaches, and good cooperation with a larger partner [44].
— United Arab Emirates: The country has initiated a structured approach involving preparation by experts from countries with large, established nuclear power programmes of a comprehensive roadmap at the outset of planning for nuclear power [45].
— Spain: While operating disposal facilities for LLW and VLLW, and performing research on geological disposal in foreign underground research facilities and within Euratom framework research programmes, also including studies on advanced fuel cycles, a decision on siting a national geological repository has been postponed for several decades [46].
— Czech Republic: The country, with a relatively small nuclear power programme (currently six reactors), has operated repositories for institutional and nuclear power plant waste since the mid 1950s. It has initiated siting of a geological repository, which is to be commissioned in 2065, and supports studies regarding advanced fuel cycles [47].

7.4. WHAT CAN THE NUCLEAR COMMUNITY DO TO HELP COUNTRIES EMBARKING ON NUCLEAR POWER ADDRESS WASTE MANAGEMENT CHALLENGES?

Acting to fulfil one part of its missions — to assist in planning for and using nuclear science and technology for various peaceful purposes, including the generation of electricity – the IAEA has, for many years, run activities aimed at helping countries with small or newly established nuclear power programmes. These include: formulating safety standard requirements and guidance and issuing technical publications; arranging conferences, workshops and training; conducting peer reviews; and distributing and sharing information through various networks, databases and meetings. Recently, as pointed out in Section 1, the IAEA has also convened groups of experts who have produced high level guidance that is invaluable for all countries with small or new nuclear power programmes [5–7]. Much of the work focuses on the principal component of a nuclear power programme, namely the construction and operation of power reactors. However, the fact that waste management issues, especially the challenge of safe disposal of spent fuel and HLW, are perceived in many countries as having been, to some extent, neglected may still be a major hurdle that countries with new nuclear power programmes must overcome. For this reason, it is appropriate that increased emphasis be placed on back end issues at this time. Critical issues that involve all nuclear power programmes however large or small include the following:

(a) Availability of waste management options: Processing, storage and disposal facilities for LLW and ILW have been operated for more than half a century; thus, the technology is proven, offering a wide spectrum of solutions. Waste storage has become a common operation using standard facilities addressing both safety and security requirements. Some countries have developed and operated conditioning and storage facilities for HLW; spent fuel storage, either wet or dry, is a part of all programmes utilizing nuclear reactors. Regarding disposal, near surface and subsurface options have been developed for different local and climatic conditions and waste inventories. Recently, VLLW disposal facilities have been put in operation, offering cost effective and safe solutions; ILW disposal has also been demonstrated at full scale.

(b) Consensus on geological disposal: A key issue is acceptance by the public that geological disposal can be carried out safely. Operation of the first national repositories for spent fuel and HLW will help here, and it is expected that this will take place around 2020. Meanwhile, encouraging countries with nuclear power programmes to formally recognize that geological disposal is a safe solution and to commit to a disposal strategy will be a useful step. The Joint Convention is a good step in this direction. The European Union has introduced requirements for formulating national strategies for siting and constructing repositories [11]. Today, there is broad consensus among countries with nuclear power programmes that geological disposal represents the safest and most suitable option for high level radioactive waste. The nuclear community should, however, continue to spread this key message to other public and political groups that remain sceptical.

(c) Encourage sharing of knowledge and experience: A country with a new nuclear power programme will have no need for an operating geological disposal facility for some decades into the future, since it must first accumulate a sufficient inventory of spent fuel or HLW. However, disposal of operational waste will require a solution much earlier, and planning has to start early, as well as provision of adequate financial and human resources. In this situation, the type of waste management oriented activities that the nuclear community can most usefully pursue in order to help countries with new nuclear power programmes include encouraging the exchange of knowledge and transfer of experience by:
    - Supporting training activities focused on the safe handling and treatment of radioactive waste;
    - Organizing relevant conferences and workshops that reinforce a functioning network of experts that can share their knowledge;
    - Providing services to countries with new nuclear power programmes that have not yet established sufficient national competencies.

(d) Support for multinational initiatives: If only one or a few reactors are to be introduced, then the costs of a geological national disposal facility may decrease the economic competitiveness of nuclear energy sources. Fixed costs of national management of SNF (storage, disposal) are high, and for countries with small nuclear power programmes, they may become a significant financial burden. Therefore, some countries are seeking a shared option. If available in the future, multinational solutions might then allow countries with small or new nuclear power programmes to have access to safe and economically effective storage and disposal facilities.

7.5. WHAT CAN NEW NUCLEAR COUNTRIES DO TO ADDRESS WASTE MANAGEMENT CHALLENGES?

Countries with small or new nuclear power programmes should not neglect waste management issues when establishing or expanding their programmes; a wait and see approach that postpones any actions will not suffice. The time required by countries with established programmes to have a complete back end route, including disposal, has been shown to be measured in decades. Furthermore, the public, politicians and regulatory bodies will expect — from the very outset of planning — a concrete roadmap that gives confidence that all necessary waste management facilities will be available when required. Most important in the framework of the current publication is that a country embarking on nuclear power has a comprehensive strategy (including target implementation dates) relating to all of its waste management activities.

The early activities are relatively straightforward, since they relate mainly to treatment and storage of all types of radioactive waste. These are technologies that are well tried and can be easily implemented, if adequate resources are made available. The biggest challenge concerns planning for disposal, in particular, disposal of spent fuel and HLW in geological repositories.

In the situation described, further activities that can help countries embarking on nuclear power to address the waste management challenges that they face include the following:

- As specified in the Joint Convention, it is necessary to establish appropriate infrastructure and regulatory systems for dealing with waste management. The infrastructure is to be built in accordance with a long term national policy of radioactive waste and spent fuel management.
- The availability of adequate funding is to be ensured by establishing structured and transparent financing schemes.
- In principle, every country running or starting up a nuclear power programme needs to have a baseline strategy that involves all waste management operations being carried out at a national level, i.e. to rely from the outset on the emergence of multinational options is not prudent. This principle, and its impact of possible life cycle costs, needs to be borne in mind by any country contemplating the introduction of nuclear power.
- The reference integrated strategy (or strategies) needs to go through to the disposal stage, even if this is far into the future.
- It would be prudent for countries embarking on nuclear power to include construction of on-site waste management facilities (processing, storage) into the nuclear power plant bidding process and plan availability of off-site facilities in accordance with capacities and lifetime of on-site facilities.
- From the outset, it is necessary to have a public information and consultation process that can help increase understanding between nuclear facility operators and stakeholders.
- Transfer of knowledge and specific training activities are both important. The areas to be addressed include not only basic nuclear education and the obvious practical activities relating to safe and secure waste treatment and storage, but also the key issue of strategic planning. Establishing a credible, flexible, overarching waste management strategy, and within this, a technically and socially acceptable siting strategy for waste management facilities is crucial and requires multidisciplinary input. Ideally, experience with modern decision aiding techniques will be built up.
- The IAEA, since its establishment, has created a common safety, security and technological environment based on international experience and consensus on important requirements on nuclear safety and security, radiation protection and safety assessment methodologies. Countries embarking on nuclear power need to make efforts not only to stay abreast of such developments, but also to influence them in cases where decisions may be taken that are more in the interest of countries with advanced nuclear power progress.
- Standardization of designs for waste storage facilities, transport systems and disposal systems is also a process that is ongoing in countries with developed nuclear power programmes, and, as in the above case, countries embarking on nuclear power would be well advised to stay abreast of such developments, especially if cost optimization is a feature of the process.
- Starting up a siting programme aimed at identifying disposal facility sites that are technically suitable and also socially acceptable is a sensitive task that has often, in the past, been deferred in order to avoid public opposition. However, the siting process is very long, and the initial phases are not very resource intensive, so that a country with a new nuclear power programme can certainly begin to address the issue.
- A forum explicitly for exchanging views and information between countries with small or new nuclear power programmes could be of value to both. Countries with larger programmes already have such forums (e.g. EDRAM [48], the Implementing Geological Disposal of Radioactive Waste Technology Platform [49] or the EU Club of Agencies) that allow in-depth exchanges. Countries with small nuclear power programmes might benefit from similar activities rather than engaging only with countries with larger programmes that are providers of commercial services.
- To select an optimal strategy, countries may follow a dual track approach consisting of developing national waste disposal facilities and, at the same time, studying possibilities for developing multinational, shared ones. For this, disposal technologies that are safe and cost efficient enough to allow their implementation can be transferred from countries with established nuclear power programmes. This is, for example, a goal of the European Commission's CATT project [50].

In implementing their national disposal programmes, countries building their waste and spent fuel infrastructure are advised to consider adequately addressing the success factors for spent fuel and waste management as presented in Annex III.

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Annex I

EXPERT OPINION ON KEY CHARACTERISTICS OF POTENTIAL BACK END STRATEGIES FOR SPENT FUEL AND HIGH LEVEL WASTE[1]

	Safety	Security and non-proliferation	Economics
A: National storage and disposal (early or late) of spent fuel	Away-from-reactor wet or dry storage have both been demonstrated to be safe for many decades. Adequate storage capacity of spent fuel in wet or dry facilities needs to be prepared or planned for the lifetime production of the reactor. The safety of well sited and constructed geological repositories is very widely accepted in technical circles.	It has been argued that wet stores are more of a security risk, but this view has been contradicted by the US Nuclear Regulatory Commission and other regulatory bodies. Safeguard measures are well established for both. Long term surface storage of either type presents a higher security risk than moving the waste underground into temporary stores or final repositories.	Pool storage at the reactor is the most economical approach during the reactor lifetime. If extra storage is required, dry storage is the commonly chosen method, since the associated costs rise incrementally. Early implementation of a geological disposal facility is ruled out by the 40–50 year cooling period normally foreseen for the spent fuel. Early implementation of a geological disposal facility may be ruled out for countries with small nuclear power programmes because insufficient waste is being accumulated to make the operation economically feasible.
B: Spent fuel reprocessing abroad, recycling nationally or abroad and waste disposal nationally	Basically the same as above. There is little significant difference in the safety levels between spent fuel and HLW repositories. However, international transport introduces an additional safety risk.	International transport introduces an additional security risk. If the recycled plutonium is not returned to the customer country, the security risk associated with plutonium transport is avoided, while the one associated with HLW transport still needs to be considered.	The economics of the reprocessing and recycling should be considered in terms of full life cycle costs as a near term expenditures could be viewed as cost restrictive for countries with small or new nuclear power programmes. This situation might change if fast reactors are introduced around 2050. Transport costs (spent fuel and HLW/ILW) need to be considered. Storage capacity for returned HLW/ILW is required until a geological disposal facility is constructed. Storage of isolated uranium/plutonium will increase the costs unless it is used/sold for manufacturing new fuel. If the spent fuel or HLW can be stored in the reprocessing country for long periods, storage needs and costs in the customer country may be lower.

[1] This annex summarizes some of the observations and opinions provided by the experts involved in developing this publication, which might be taken note of when considering possible back end strategies. They do not represent an official IAEA position.

	Safety	Security and non-proliferation	Economics
C: Reprocessing, recycling and waste disposal of spent fuel abroad	Assuming a comparable level of safety at each facility, a single, larger geological disposal facility may enhance overall safety compared with many smaller facilities. If the disposal takes place in the reprocessing country, it will likely be within the scope of a large, state of the art project with a developed safety culture. If disposal is offered by a third party country, then measures must be taken to ensure the same levels of safety as expected for national programmes. International transport introduces an additional risk.	This option involves less international transport than the above. This option reduces the number of geological repositories globally, and hence may make a contribution to overall global security. If disposal is offered by a third party country, then measures must be taken to ensure the same levels of security as expected for national programmes. International supervision provides for enhanced non-proliferation control. International transport introduces an additional security risk.	Reprocessing today is too expensive to be attractive as such to countries with small or new nuclear power programmes. If a disposal option were included, then reprocessing could be more economically attractive. However, the customer country would still need a geological disposal facility, unless its other long lived waste is also accepted by the foreign disposer. Isolated uranium/plutonium needs to be used/sold for manufacturing new fuel (MOX). Spent MOX fuel will have to be disposed of nationally or managed internationally and, in any case, included in economic calculations. Disposal and transit transport fees may decrease the economic attractiveness.
D: Spent fuel national storage then disposal in a shared disposal facility	Measures must be taken to ensure the same levels of safety and security as with national disposal. International transport introduces an additional risk.	This option reduces the number of geological repositories globally and hence may make a contribution to overall global security. Spent fuel is more of a security concern than HLW, so that this option is less favourable than the previous one from a security point of view. International supervision provides for enhanced non-proliferation control. International transport introduces an additional risk.	The economies of scale in disposal facility implementation imply that this is an economically favourable approach. However, the user countries would still need a geological disposal facility, unless their other long lived waste is accepted by the shared disposal facility. Disposal and transit transport fees may decrease the economic attractiveness.
E: Fuel leasing	Implies transport beyond national borders for fuel and spent fuel that may also be associated with greater distances, and the corresponding transport risks need to be considered. Supplier countries may implement repositories sooner, given the larger inventories accumulated.	Avoids accumulation of spent fuel at many places throughout the world. International supervision provides for enhanced non-proliferation control. International transport introduces an additional risk.	Depends on pricing arrangements of fuel suppliers. Transport costs and transit transport fees may decrease the economic attractiveness.

	Safety	Security and non-proliferation	Economics
F: Retention of spent fuel as a valuable commodity	Resources to ensure maintenance and possibly refurbishment of stores must be made available over long periods if safety levels are to be maintained. With long storage times, further treatment or disposal of the stored spent fuel may present lower risks because of the additional decay of heat and radioactivity. For long term storage, the continuing integrity of the fuel and facility (ageing prevention) needs to be ensured and demonstrated prior its implementation.	This strategy, if followed by many countries, is obviously less attractive from a security point of view than options that gather spent fuel in fewer places and, even better, move the hazardous materials underground at earlier times. Longer storage times imply longer security risks.	In the short term, this strategy is economically attractive for countries with small nuclear power programmes, provided that they ensure that the reactors have adequate on-site storage and that a financing system is established to ensure the availability of adequate funds. The long term economic attractiveness will depend on when fast reactors become commercially operated and will need to use spent fuel from other countries. Thus, this option contains significant uncertainties.
G: National storage and disposal of operational waste	This is the normal, practically implemented case with clearly demonstrated safety approaches.	Low security threat, practical measures have been developed and implemented.	This is the normal, expected case with a low economic burden.
H: Multinational storage and disposal of operational waste	As above, transport may increase safety concerns.	As above, transport increases security threats. International supervision provides for enhanced non-proliferation control.	Transport and disposal fees need to be considered in economic analysis.

	Political	Legal	Societal
A: National storage and disposal (early or late) of spent fuel	Early national disposal is the advice mostly given by international bodies, in particular, the European Commission. The national responsibility for managing waste and spent fuel is also a central message in the Joint Convention on the Safety of Spent Fuel and on the Safety of Radioactive Waste Management, although it also recognizes sharing facilities as an option. Politically, this strategy is often considered easier to implement than multinational solutions, as it avoids debate on the ethics of possible waste import or export. Although early national disposal is impractical for countries with new nuclear power programmes, credible concepts for future disposal may be required to achieve political acceptance of new nuclear power plants. Delaying disposal for any reason is not to be taken as a 'wait and see' approach: timing of preparatory work is required (and in EU Member States, it is requested by the directive).	In most countries, geological disposal is based on a legal requirement or at least is a policy option. Some countries and some states of the United States have imposed a legal block on reactor construction until demonstrated disposal routes are available.	In many countries, opinion polling indicates that the public generally support national solutions, provided that these are not implemented in their locality. The fundamental safety of geological disposal is acknowledged by the technical community, but in some countries, there are still large sectors of the public that are not fully convinced. In any case, a programme of public involvement providing for discussions of waste management needs to be part of any new nuclear power programme already in the initial stages.
B: Spent fuel reprocessing abroad, recycling nationally or abroad and waste disposal nationally	Reprocessing abroad is politically acceptable in most countries, and there are foreign service providers. The management of fissile material is more sensitive and the easier approach would be to have MOX fuel fabricated in the country that provides reprocessing services. The arguments for national waste disposal are the same as above.	In the reprocessing countries, the position is often that the HLW must be returned. Exceptions are made by the Russian Federation for some fuel that has been supplied by the Russian Federation. Fuel suppliers may restrict or pose conditions such as prior consent for transfer to the third countries. This may also restrict fuel reprocessing. International financial liabilities for a sustainable decommissioning and RWM programme need to be defined. The European Union does not allow disposal of spent fuel outside the territory of EU Member States.	In some countries, there has been public opposition to foreign reprocessing contracts, based mainly on the argument that current reprocessing technologies are not environmentally friendly because of their radioactive emissions. There have also been quite strong objections for proliferation reasons.

	Political	Legal	Societal
C: Reprocessing, recycling and waste disposal of spent fuel abroad	Unless other restrictions are implemented (EU directive), disposal abroad would be a politically acceptable solution for most countries with new nuclear power programmes, provided that the hosting country for the disposal facility is willing and politically stable. In most of the reprocessing countries, retention of foreign waste for disposal is politically problematic.	A few countries have laws that would prohibit the export of their waste. More common is a ban on the import of radioactive waste. International financial liabilities for a sustainable decommissioning and RWM programme need to be defined.	In the reprocessing countries, there is opposition to such a strategy. The public in the customer country would be unlikely to object to the non-return of waste, but some may object to reprocessing as such, as mentioned above.
D: Spent fuel national storage then disposal in a shared disposal facility	This is politically acceptable, provided that a willing host country (or countries) for a shared disposal facility can be identified. EU Member States restrict this option for their territory.	In various countries, national laws on import and export of radioactive waste would need to be amended. International financial liabilities for a sustainable decommissioning and RWM programme need to be defined. Selection of host countries is limited to EU Member States by the directive.	Provided that the shared disposal facility is assured to be state of the art and that there is national and local acceptance of the shared disposal facility in the hosting country, this option would be acceptable to all users.
E: Fuel leasing	Political support for this option results from the fact that fissile materials are concentrated in fewer countries and that these are the major fuel cycle countries.	With the exception of EU Member States, there are no legal hurdles, provided that returned spent leased fuel is not regarded as a waste import.	The returned spent fuel must be seen as a resource rather than a waste product if public opposition to waste import is to be avoided.
F: Retention of spent fuel as a valuable commodity	This can be a national policy decision if prospects for future use of the stored fuel are high enough. If large numbers of countries introduce nuclear power and adopt this strategy, concerns may arise in the international community about spent fuel being accumulated and stored for decades at numerous locations around the world.	There are no direct legal hurdles to this approach, but in some countries, planning for storage without having a disposal strategy has led to opposition or legal challenges to the licensing of nuclear reactors.	Public opposition to spent fuel storage facilities may increase if centralized away-from-reactor stores become necessary or if the at-reactor stores are required to be maintained even after the ~50 years of reactor operation are past.

	Political	Legal	Societal
G: National storage and disposal of operational waste	This is the normal, expected case; political opposition is not to be expected, although groups opposed to nuclear power have delayed such projects.	Nuclear facilities are regulated according to the national legislative system. The measures might incorporate community veto rights.	This is the normal, expected case; disposal facility siting will be the biggest challenge
H: Multinational storage and disposal of operational waste	The political situation here will be very similar to that for multinational storage and disposal of spent fuel and HLW.	The legal situation here will be very similar to that for multinational storage and disposal of spent fuel and HLW. International financial liabilities for a sustainable decommissioning and RWM programme need to be defined.	The societal attitude will be similar to that for multinational storage and disposal of spent fuel and HLW.

Annex II

OVERVIEW OF NATIONAL RADIOACTIVE WASTE MANAGEMENT STRATEGIES IN COUNTRIES WITH SMALL NUCLEAR POWER PROGRAMMES[1]

Country	Nuclear power plant capacity (net MW installed)	Operational waste policy	SNF policy	LLW–ILW disposal facility	HLW disposal facility	RWM agency	Comment
Argentina	935	Disposal (national, centralized facility)	Decision on reprocessing deferred until 2030	Siting	Feasibility study	No	
Armenia	375	Storage	Storage	No activity	No activity	No	National policy and strategy to be developed
Belgium	5926	Disposal (national)	Disposal (national)	Site selected (near surface)	Research in underground laboratory performed	ONDRAF/NIRAS	
Brazil	1884	Disposal (national)	Decision on reprocessing deferred	Site screening, conceptual design completed	Decision pending	No	RWM agency to be established
Bulgaria	1906	Disposal (national)	Reprocessing and long term storage of HLW in the Russian Federation	Facility sited (near surface for nuclear power plant waste) Operational (near surface for institutional waste)	No activity	DPRAO	ERDO member New SNF management policy being developed
Czech Republic	3678	Disposal (national)	Disposal (national)	Operational (near surface for nuclear power plant waste) Operational (mined cavity for institutional waste)	Site selection initiated	RAWRA	

[1] Countries with <10 000 MW(e) installed capacity.

Country	Nuclear power plant capacity (net MW installed)	Operational waste policy	SNF policy	LLW–ILW disposal facility	HLW disposal facility	RWM agency	Comment
Finland	2716	Disposal (national)	Disposal (national)	Two operational (mined cavities)	Site selected, construction of confirmation laboratory in progress	POSIVA (responsible for the development of a deep geological disposal facility)	Application for the construction licence for the HLW disposal facility planned for 2012
Hungary	1889	Disposal (national)	Pending decision, storage for ~50 years	Operational (near surface) Under construction (mined cavity)	Site selection initiated	PURAM	
Mexico	1300	Disposal (national)	At-reactor storage	Planning stage	No activity	No	National policy and strategy under development
Netherlands	487	Decision deferred for 100 years	Decision deferred for 100 years	Decision deferred	Decision deferred	COVRA	ERDO member
Pakistan	425	Disposal (national)	Storage	Siting	No activity	No	National policy and strategy drafted
Romania	1300	Disposal (national)	Storage for 50 years	Disposal facility sited (near surface for nuclear power plant waste) Operational (mined cavity for institutional)	No activity	ANDRAD	ERDO member
Slovakia	1816	Disposal (national)	Disposal (national)	Disposal facility in operation (near surface)	Site screening initiated	No	ERDO member RWM agency to be established Multinational shared facility possible

Country	Nuclear power plant capacity (net MW installed)	Operational waste policy	SNF policy	LLW–ILW disposal facility	HLW disposal facility	RWM agency	Comment
Slovenia	666	Disposal (national)	Disposal (national) Decision by 2030	Site selected	Strategy accepted	ARAO	ERDO member Multinational shared HLW disposal facility possible
South Africa	1800	Disposal (national)	Disposal (national)	Disposal facility in operation (near surface)	No activity	No	RWM agency to be established
Spain	1014	Disposal (national)	Disposal (national)	Disposal facility in operation (near surface)	Prolonged storage, siting postponed	ENRESA	Near surface disposal facility for very low level waste (VLLW) in operation
Sweden	9311	Disposal (national)	Disposal (national)	LLW disposal facility in operation (mined cavity)	Disposal facility sited, an underground research facility in operation Application for a construction licence released	SKB	Near surface repositories for VLLW in operation at nuclear facilities
Switzerland	3263	Disposal (national)	Disposal (national)	Siting	Siting	Nagra	Co-siting of LLW and HLW facility considered

Annex III

SUCCESS FACTORS FOR SPENT FUEL AND WASTE MANAGEMENT

Success factor 1: Long term political commitment to resolve the spent fuel and waste issue;

Success factor 2: National strategy and discipline;

Success factor 3: Well defined liabilities and roles;

Success factor 4: Early established funding system;

Success factor 5: Agreement of the local community regarding hosting the repository in a stepwise licensing process;

Success factor 6: Regulatory body's early involvement in the project and strategic planning to allow development of regulatory approach parallel with repository development and in analogy with nuclear power plant safety regulations;

Success factor 7: Well structured, stepwise, open and defendable implementation programme using a graded approach and 'rolling documents' strategy;

Success factor 8: Good safety culture and importance of dialogue between the regulatory body and the implementer based on comparable levels of technical competence;

Success factor 9: Transparency and engagement of public, domestic, and international scientific and technical communities.

ABBREVIATIONS

CANDU reactor	Canada deuterium–uranium reactor
DSRS	disused sealed radioactive source
ERDO	European Repository Development Organisation
HLW	high level waste
HWR	heavy water reactor
ILW	intermediate level waste
LLW	low level waste
LWR	light water reactor
MOX	mixed oxide
NORM	naturally occurring radioactive material
PWR	pressurized water reactor
RWM	radioactive waste management
SAPIERR	Support Action: Pilot Initiative for European Regional Repositories
SNF	spent nuclear fuel
VLLW	very low level waste
VSLW	very short lived waste

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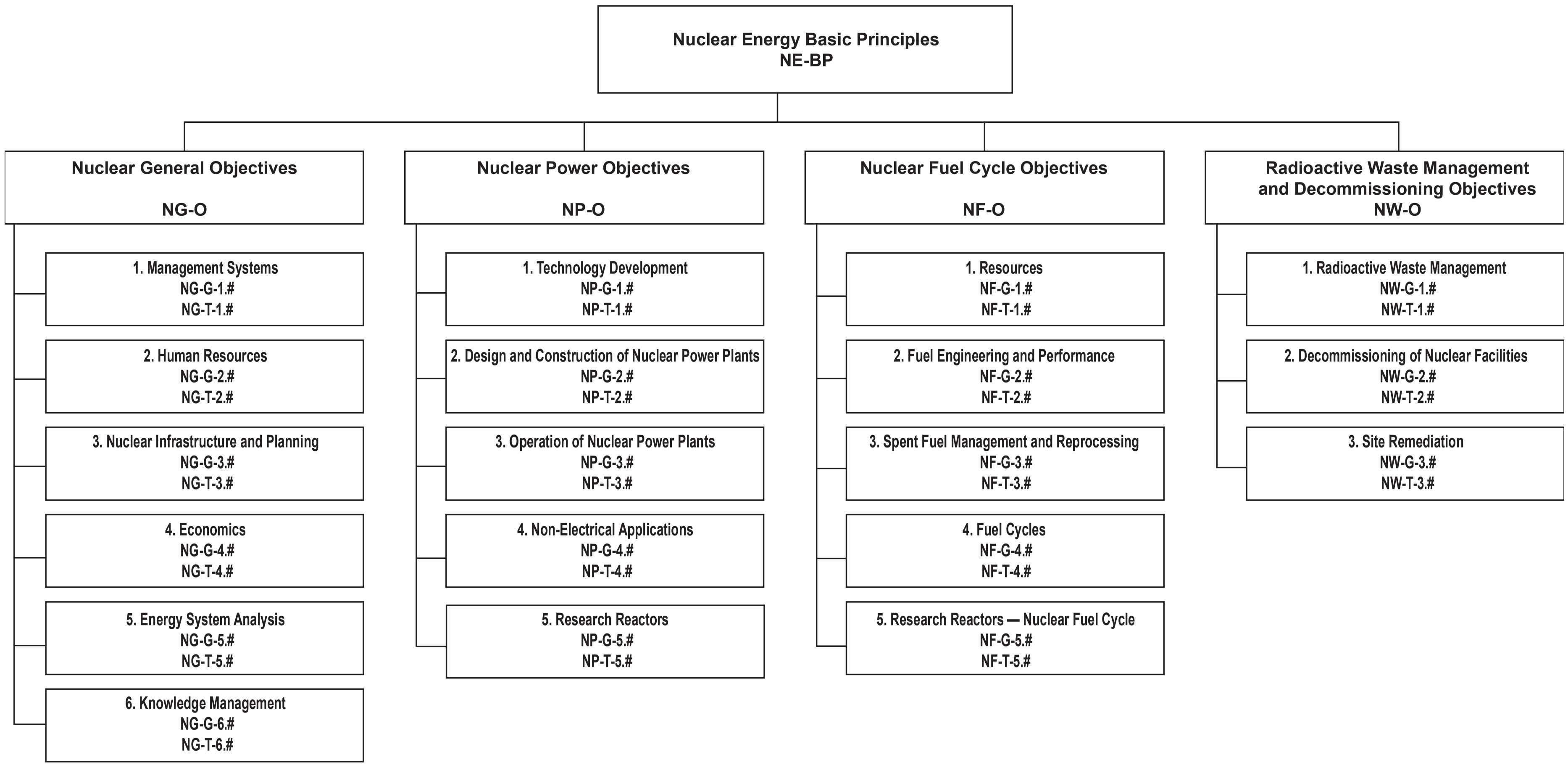

Key

BP: Basic Principles
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