IAEA Nuclear Energy Series

No. NW-T-1.14

Basic Principles

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Status and Trends in Spent Fuel and Radioactive Waste Management

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IAEA NUCLEAR ENERGY SERIES PUBLICATIONS

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STATUS AND TRENDS IN SPENT FUEL AND RADIOACTIVE WASTE MANAGEMENT

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA NUCLEAR ENERGY SERIES No. NW-T-1.14

STATUS AND TRENDS IN SPENT FUEL AND RADIOACTIVE WASTE MANAGEMENT

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2018

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tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
January 2018
STI/PUB/1799

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Status and trends in spent fuel and radioactive waste management / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2018. | Series: IAEA nuclear energy series, ISSN 1995–7807 ; no. NW-T-1.14 | Includes bibliographical references.
Identifiers: IAEAL 18-01137 | ISBN 978–92–0–108417–0 (paperback : alk. paper)
Subjects: LCSH: Radioactive waste management. | Spent reactor fuels. | Radioactive waste disposal.
Classification: UDC 621.039.7 | STI/PUB/1799

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.

This publication presents the outcomes of the Status and Trends project, undertaken by the IAEA in collaboration with the European Commission and the OECD Nuclear Energy Agency. The project was launched in June 2014 and completed in June 2016. Consideration will now be given to publishing regular updates, most likely to be on a three year basis corresponding to the reporting cycle of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (Joint Convention).

This publication provides an overview of the current status and trends in spent fuel and radioactive waste management, and includes information on current inventories, expected future waste arisings and strategies for the long term management of these materials. The information provided in this publication is based primarily on the National Profiles submitted by each of the participating Member States, using a common reference date, and data presented in the reports to the Fifth Review Meeting of the Contracting Parties to the Joint Convention. The National Profiles are provided on the CD-ROM accompanying this publication.

The IAEA is grateful for the participation of all those who contributed in the preparation and drafting of this publication, in particular H. Forsstrom (Sweden), who chaired the Joint Working Group of representatives from the participating Member States. The IAEA officers responsible for this publication were P.J. O'Sullivan of the Division of Nuclear Fuel Cycle and Waste Technology and J.G. Kinker of the Division of Planning, Information and Knowledge Management.

EDITORIAL NOTE

CONTENTS

SUMMARY

Radioactive waste is a byproduct of nuclear power generation and other uses of radioactive material. The waste comprises various forms and materials, with different radioactivity levels and half-lives. Radioactive waste needs to be handled safely and eventually disposed of in a safe manner. Acceptable disposal routes depend on the level of radioactivity and established preferences and practices in different countries. Some waste contains such low levels of radioactivity that it can be released from regulatory control and disposed of as non-radioactive waste. However, for radioactive waste that presents a long term risk to people and the environment, its endpoint is placement in an appropriate package and disposal in a suitably engineered, multibarrier facility.

This publication provides an overview of current global inventories of spent fuel and radioactive waste, current arrangements for their management, and future plans for their ultimate disposal where appropriate. Spent fuel is generated only by States operating nuclear power plants or research reactors, whereas radioactive waste is generated in all States producing or using radioactive material in, for example, the nuclear fuel cycle, defence activities, medicine, industry and research. It is intended to update this publication at regular intervals, following the reporting schedule for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.

Institutional, organizational and technical aspects of spent fuel and radioactive waste management are explored, including: legal and regulatory systems; organization of waste management activities and associated responsibilities; and strategies and plans for ongoing management of different types of spent fuel and radioactive waste from its generation through conditioning and storage to disposal. This publication compiles the quantities of spent fuel and radioactive waste which currently exist and explores forecasts for the coming decades. Significant trends and the corresponding challenges in the management of spent fuel and radioactive waste are also discussed.

Inventory estimates of spent fuel and radioactive waste in the world are based on information in the National Profiles provided by 47 participating Member States and provided on the CD-ROM accompanying this publication. Data are supplemented where necessary by published reports to the Joint Convention. For most cases, the information provided corresponds to the end of December 2013; the data are based on information from States accounting for almost 95% of all nuclear power reactors in the world. On this basis, there is an estimated 250 000 t HM of spent fuel in storage worldwide and 120 000 t HM of reprocessed spent fuel. The current total global inventory of solid radioactive waste is approximately 35 million m^3, of which 28.5 million m^3 (82% of the total) has been disposed of permanently and a further 6.3 million m^3 (18%) is in storage awaiting final disposal. More than 98% of solid waste is classified as being very low or low level waste in volume terms, with most of the remainder being intermediate level waste. In terms of total radioactivity, the situation is fully reversed, with approximately 98% of the radioactivity being associated with intermediate and high level waste. This publication also provides volumes of liquid radioactive waste, both disposed of and in storage.

It is evident that significant progress is being made globally in formulating national policies and strategies and in implementing legal and regulatory systems that define responsibilities for the ongoing safe management of spent fuel and radioactive waste. Most States expect to dispose of their waste in facilities located on their territories, with the main focus of international cooperation being on technology development. Disposal facilities for very low level and low level waste are already in operation in several countries. However, in many others, particularly those with small volumes of radioactive waste, disposal options still have to be developed. The most important remaining challenge is the development of disposal facilities for high level waste and spent nuclear fuel considered as waste. In this context, public acceptance is very important. Significant progress is being made in a few countries, such as a construction licence being granted in Finland in November 2015. However, programmes are progressing slowly in many others.

1. INTRODUCTION

1.1. BACKGROUND

Spent fuel and radioactive waste are byproducts of nuclear power generation and other uses of radioactive material in medicine, industry and research. Spent fuel is highly radioactive and needs to be handled with shielding and cooling. It also contains substantial amounts of long lived isotopes, which means that the fuel (if not reprocessed) and its components need to be disposed of with appropriate care: IAEA guidance [1], and the policy of most States, is to dispose of it in a geological repository, typically at depths of several hundred metres. The radioactive waste comprises various forms and materials, with different radioactivity levels and half-lives. The requirements on the management and disposal of the radioactive waste will thus depend on whether it is classified as high (HLW), intermediate (ILW), low (LLW) or very low level waste (VLLW). In particular, the final disposal of the waste may range from geological disposal for HLW to near surface trench disposal for VLLW. The activity level and the nature of radionuclides in the waste also determine the conditioning needs for the waste before disposal or, as the case may be, release from regulatory control.

There is currently no authoritative publication that systematically and periodically summarizes the global status and trends of inventories and programmes for spent fuel and radioactive waste management. Some publications cover the subject on a partial or regional basis. The European Commission has published such information every three years since 1992 (see Ref. [2]). The OECD Nuclear Energy Agency (OECD/NEA) publishes profiles and reports about radioactive waste management programmes in members[1] and also an annual report on nuclear energy data on members (Brown Book [3]).

The IAEA has been actively collecting information on radioactive waste inventories and management practices since 2000 and has issued a number of publications based on the IAEA Net Enabled Waste Management Database (NEWMDB). In 2007, the IAEA released estimates on global inventories of radioactive waste and other radioactive materials, which included defence and nuclear weapons data as well as information from nuclear power production [4]. The publication drew on various resources but was principally based on extrapolations from global nuclear energy statistics, rather than on nationally reported information.

This publication is a collaborative project between the IAEA, the European Commission and the OECD/NEA to complement the information gathered from different initiatives around the world. The analysis presented is based on information as of December 2013 to promote compatibility with the information in reports presented in 2015 under the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (Joint Convention) [5] and those provided to the European Commission in 2015 in accordance with Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste (Euratom Waste Directive) [6].

On completion of the current initiative, the IAEA, the European Commission and the OECD/NEA will give consideration to continuing the initiative to future reporting cycles under these legal instruments, including pursuing efforts to harmonize and minimize the reporting requirements for States and avoiding duplication of effort wherever possible. This publication provides a valuable starting point for such future publications, which are likely to be produced every three years, in synchrony with the reporting cycles associated with the above legal instruments. A significant focus of this publication is on current inventories of spent fuel and radioactive waste, to provide a sound basis for comparison in future editions.

Approximately 80% of States with operating nuclear power plants submitted reports, representing almost 95% of all nuclear power reactors in the world. Further improvement in the extent of data coverage and an increasing focus on future waste arisings and on trends in management practices are expected in future editions. Meanwhile, this publication provides an extensive overview of the management of spent fuel and radioactive waste worldwide and of the quantities involved. The volumes of different types of waste give an indication of the magnitude of the work needed for managing and disposing of the material. A large volume does not, however, necessarily correspond to a large risk. When determining the potential risks of different material, the radioactivity content in particular needs to be considered.

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[1] See www.oecd-nea.org/rwm/profiles

1.2. OBJECTIVE

The purpose of this publication is to provide a global overview of the status of spent fuel and radioactive waste management concerning inventories, programmes, current practices, technologies and trends. It provides overviews of national arrangements and programmes for spent fuel and radioactive waste management, of current waste and spent fuel inventories and estimates of future amounts. International and national trends in these areas are also addressed.

This publication provides an initial compilation of global data, with a particular focus on the current status of spent fuel and radioactive waste management. The data reported are fully dependent on the input from the States and by the assumptions made for transforming these data into a global framework.

1.3. SCOPE

This publication provides complementary information to the Summary Report from the Fifth Review Meeting of the Contracting Parties to the Joint Convention [7], and addresses the following: the institutional, legal and regulatory frameworks for the management of spent fuel and radioactive waste; spent fuel and radioactive waste management programmes, current practices and technologies; and spent fuel and radioactive waste inventories and forecasts. The inventories and forecasts include spent fuel and radioactive waste that has been, or is forecasted to be, generated or managed by the following types of facility:

(a) Nuclear power plants, research reactors, fuel cycle facilities, industrial facilities, and medical and research facilities that are currently in operation or in temporary shutdown status;
(b) Facilities being decommissioned or which are planned to undergo decommissioning;
(c) Spent fuel and radioactive waste processing and storage facilities (e.g. treatment facilities, spent fuel pools, dry storage facilities for spent fuel, solid waste storage facilities and storage tanks for liquid waste);
(d) Radioactive waste disposal facilities (including both operating facilities and closed facilities);
(e) Other facilities or waste sources included in national radioactive waste management programmes.

The types of radioactive waste not included are the following:

— Exempt waste, which para. 2.2 of IAEA Safety Standard Series No. GSG-1, Classification of Radioactive Waste [1], defines as “Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes”.
— Very short lived waste (since this is typically held for decay, then released).
— Authorized effluent releases.
— Radioactive materials and products other than spent fuel that have not been declared as radioactive waste.
— Naturally occurring radioactive material (NORM) residues (although some States have reported NORM waste in the National Profiles).

If it is included in the reported national radioactive waste inventory, the publication also includes waste from extractive industries (e.g. uranium and other types of mining) and radioactive waste from military and defence activities. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.4. STRUCTURE

This publication provides an overview of current spent fuel and radioactive waste management internationally and provides a compilation of policies, strategies and spent fuel and radioactive waste quantities on a regional and global scale. This is based on information in the National Profiles supplied, which are to a large extent based on information provided by the State in their report to the Joint Convention. Section 2 presents the relevant international legal instruments and IAEA safety standards governing spent fuel and radioactive waste management.

Section 3 outlines the sources of spent fuel and radioactive waste. Sections 4 and 5 explore the frameworks for managing such waste and the management programmes in place, respectively. Section 6 describes the inventories. Sections 7 and 8 present future forecasts, and trends and challenges, and Section 9 concludes.

The National Profiles are on the attached CD-ROM accompanying this publication. The structure of the National Profiles and the preparation of this publication were developed by a joint working group on spent fuel and radioactive waste established by the IAEA, the European Commission and the OECD/NEA. The collection of information on spent fuel and radioactive waste involves several challenges, such as the use of different waste classification in different countries, different status of waste conditioning and different stages of development of waste management systems. This gives rise to uncertainties, which are discussed in Section 7. The sources of data include the following:

— National reports to the Joint Convention, which are produced every three years in advance of the Review Meetings of the Contracting Parties. The IAEA provides the secretariat for the Joint Convention, and the latest review meeting was held in May 2015.
— National reports to the European Commission in accordance with the Euratom Waste Directive [6]. The first reporting to the European Commission according to this directive was due in August 2015.
— Reports to the OECD/NEA providing input to the National Profiles and to other special reports on specific subjects.
— Reports prepared as input to documents by IAEA working groups.

2. INTERNATIONAL LEGAL INSTRUMENTS AND IAEA SAFETY STANDARDS

2.1. JOINT CONVENTION ON THE SAFETY OF SPENT FUEL MANAGEMENT AND ON THE SAFETY OF RADIOACTIVE WASTE MANAGEMENT

The Joint Convention [5], which entered into force in 2001, highlights the importance given to spent fuel and radioactive waste management. It is the only international, legally binding instrument on this type of waste, and Article 1 states:

“The objectives of this Convention are:

(i) to achieve and maintain a high level of safety worldwide in spent fuel and radioactive waste management, through the enhancement of national measures and international co-operation, including where appropriate, safety-related technical co-operation;
(ii) to ensure that during all stages of spent fuel and radioactive waste management there are effective defenses against potential hazards so that individuals, society and the environment are protected from harmful effects of ionizing radiation, now and in the future, in such a way that the needs and aspirations of the present generation are met without compromising the ability of future generations to meet their needs and aspirations;
(iii) to prevent accidents with radiological consequences and to mitigate their consequences should they occur during any stage of spent fuel or radioactive waste management.”

As of February 2016, there were 72 Contracting Parties to the Joint Convention [5] (see Table A–1 for a list). The Contracting Parties meet every three years to discuss the National Reports, which are subject to a peer review process.[2]

[2] Information on the Joint Convention [5], its current status, documents and results of review meetings are available at www.iaea.org/topics/nuclear-safety-conventions

2.2. COUNCIL DIRECTIVE 2011/70/EURATOM OF 19 JULY 2011 ESTABLISHING A COMMUNITY FRAMEWORK FOR THE RESPONSIBLE AND SAFE MANAGEMENT OF SPENT FUEL AND RADIOACTIVE WASTE

All 28 EU Member States are members of the European Atomic Energy Community (Euratom) and are also Contracting Parties to the Joint Convention [5]. According to the Article 2 of the Treaty establishing the European Atomic Energy Community, "the Community shall…establish uniform safety standards to protect the health of workers and of the general public and ensure that they are applied". This is reflected in Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom [8].

The Euratom Waste Directive [6], like the Joint Convention [5], ensures appropriate national arrangements for a high level of safety in spent fuel and radioactive waste management. In particular, each EU Member State is required to develop a framework and a programme for the responsible and safe management of spent fuel and radioactive waste, and to implement this programme in a planned and stepwise manner. The Euratom Waste Directive [6] is also intended to ensure adequate public information and participation in the management of spent fuel and radioactive waste.

2.3. IAEA SAFETY STANDARDS

Radioactive waste represents a potential hazard to human health and to the environment, and therefore it needs to be managed safely. Over the years, considerable experience has been gained, and based on this, the IAEA has developed a comprehensive set of safety standards applicable to radioactive waste management. Some of these standards are general, while others are directly dedicated to radioactive waste management.

The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. They are issued in the IAEA Safety Standards Series, which has three categories: Safety Fundamentals, Safety Requirements and Safety Guides. IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [9], presents the fundamental safety objective and principles of protection and safety, and provides the basis for the Safety Requirements, which establish the requirements to be met to ensure the protection of people and the environment. The Safety Guides provide recommendations and guidance on how to comply with the safety requirements. Of particular relevance for this publication are IAEA Safety Standards Series Nos GSR Part 5, Predisposal Management of Radioactive Waste [10], and SSR-5, Disposal of Radioactive Waste [11].

The safety standards are supported by numerous publications produced by the IAEA, which aim to promulgate and share current good practice in the management of spent fuel and radioactive waste throughout its life cycle. The European Commission and the OECD/NEA have also published several reports on good practice concerning these issues.

3. SOURCES OF SPENT FUEL AND RADIOACTIVE WASTE

Most industrial processes result in the generation of waste which subsequently needs to be managed safely and effectively. The operation of nuclear reactors, as well as their associated fuel cycles (uranium production, enrichment, fuel fabrication and reprocessing), generates radioactive material to be managed as radioactive waste. Radioactive waste also results from the use of radioactive materials in research, medicine, education and industry. In some countries, radioactive waste is also generated in support of defence activities. This means that practically all States have to consider the management of radioactive waste and to make sure it is managed in a safe manner with due regard to the level of radioactivity and in compliance with national regulations, often based on, or in harmony with, IAEA safety standards.

The activities connected to the safe management of radioactive waste, especially disposal, are quite different depending on the type of waste. As the radioactivity content of different types of radioactive waste varies greatly, there are different classes. Although different waste classification systems exist, the classification system used in this publication follows the definitions in para. 2.2 of GSG-1 [1], which classes waste according to the disposal route required to provide long term safety. Figure 1 illustrates the association between waste classes, activity levels and half-lives, with the boundaries between classes (shown as dashed lines) being non-quantitative — that is, ‘case specific’ factors need to be considered in deciding the applicable waste class:

(1) Exempt waste (EW): Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes.
(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 from regulatory control according to arrangements approved by the regulatory body, 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): Waste that is above clearance levels, but with 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 a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal.
(6) High level waste (HLW): Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal of HLW.

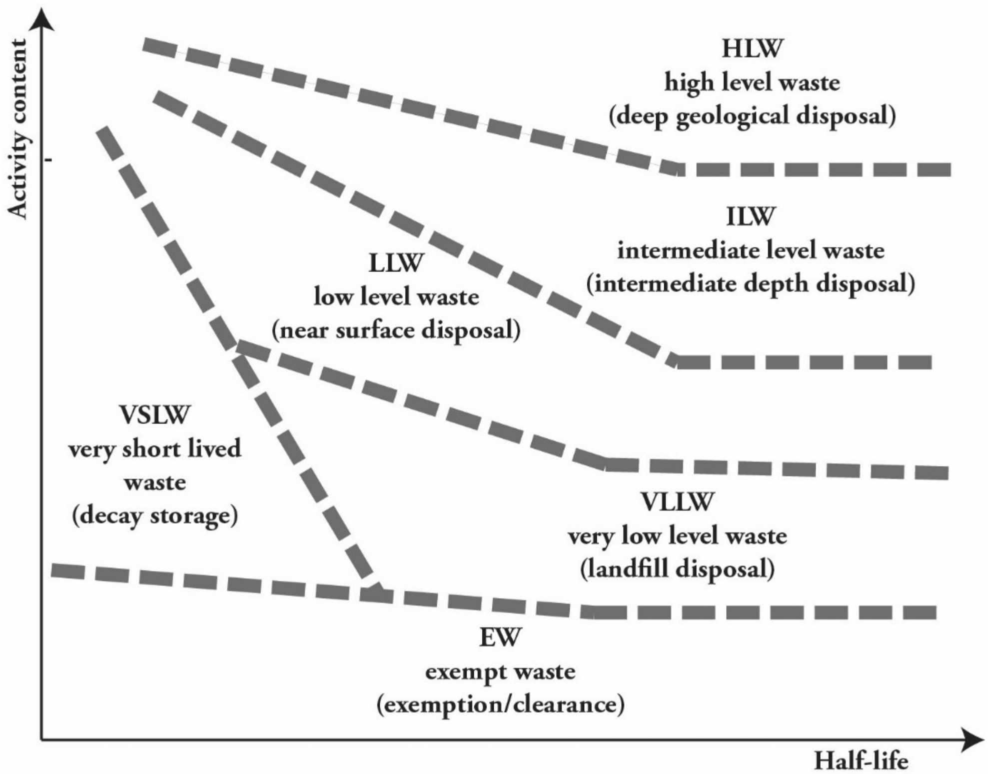


FIG. 1. Conceptual illustration of the waste classification scheme [1].

NORM can be classified as radioactive waste depending on the national waste management concept. NORM residues which arise during the mining of uranium ore and the production of uranium fuel are called mine and mill tailings (see Fig. 2). Radioactive residues with low levels of radioactivity are also generated in other mining and extraction activities, for example thorium and rare earth mining, oil extraction and even sediments from a water supply.

Some of the residue has such a low content of radionuclides that the impact to potentially exposed individuals or to society is negligible, and it can be released from regulatory control (‘clearance’) in accordance to the State’s regulations. VSLW needs only to be managed as radioactive material for relatively short periods, pending the decay of the radioactivity. With the exception of this waste class, most radioactive waste is disposed of in dedicated disposal facilities, usually being conditioned into a solid and stable form prior to disposal.

In the past, some radioactive waste was disposed of at sea, a practice which was fully abandoned in 1993 [12], although this practice generally ceased around twenty years earlier (see Section 6.5).

FIG. 2. Uranium production site of Caetité, Brazil.

3.1. SPENT FUEL AND RADIOACTIVE WASTE FROM NUCLEAR POWER, RESEARCH AND OTHER REACTORS

Today, nuclear power reactors are being operated in 30 countries (see Figs 3 and 4). In addition, Belarus and the United Arab Emirates are currently constructing their first nuclear power plants. Italy, Kazakhstan and Lithuania operated nuclear power reactors in the past, but these have been shut down. Some reactors have been completely dismantled, and the radioactive components have been handled as radioactive waste (see Table 1). There are States with research reactors and other reactors, which brings the total number of States involved to approximately 70.[3]

FIG. 3. Construction of the Sanmen nuclear power station, China (courtesy of China National Nuclear Corporation).

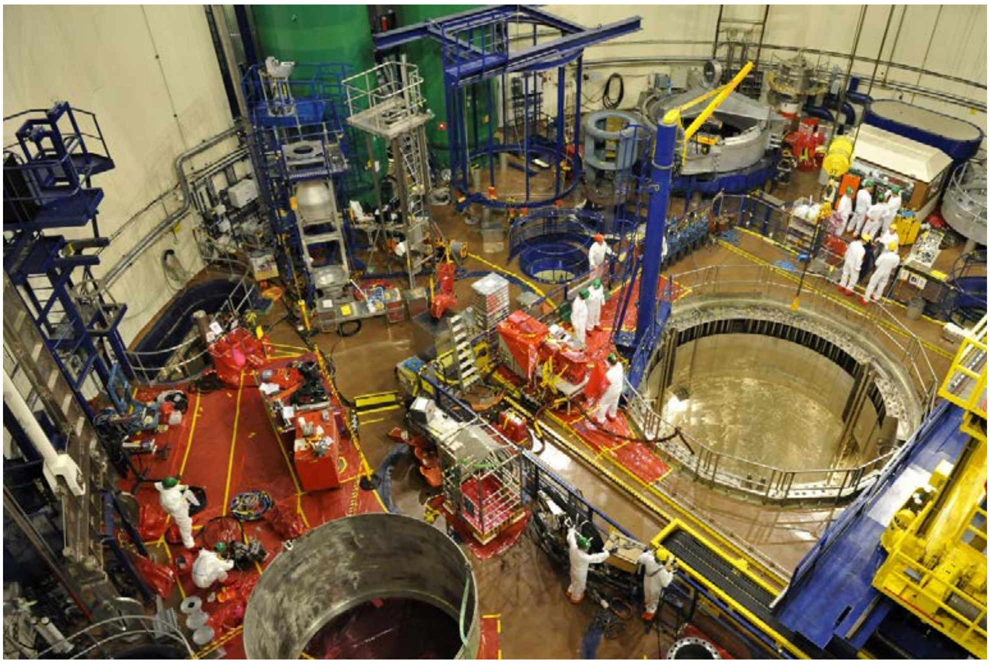


FIG. 4. Reactor hall in Loviisa nuclear power plant, Finland (courtesy of Fortum).

[3] See https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx

TABLE 1. OPERATING AND SHUTDOWN NUCLEAR POWER REACTORS, JUNE 2016

	In operation	Installed capacity (MW(e))	Shut down
Argentina	3	1 627	0
Armenia	1	376	1
Belgium	7	5 943	1
Brazil	2	1 901	0
Bulgaria	2	1 926	4
Canada	19	13 553	6
China	34	30 597	0
Czech Republic	6	3 904	0
Finland	4	2 741	0
France	58	63 130	9
Germany	8	10 728	28[a]
Hungary	4	1 889	0
India	21	5 302	0
Iran, Islamic Republic of	1	915	0
Italy	0	n.a.[b]	4
Japan	2	40 480	17
Kazakhstan	0	n.a.[b]	1
Korea, Republic of	25	23 017	0
Lithuania	0	n.a.[b]	2
Mexico	2	1 600	0
Netherlands	1	485	1
Pakistan	3	725	0
Romania	2	1 310	0
Russian Federation	35	26 053	5
Slovakia	4	1 816	3
Slovenia	1	696	0
South Africa	2	1 830	0
Spain	7	7 121	2
Sweden	9	8 849	3
Switzerland	5	3 333	1
Ukraine	15	13 107	4
United Kingdom	15	8 883	30
United States of America	99	100 013	33[c]

Source: Power Reactor Information System, World Nuclear Association and Ref. [13].

[a] In addition, three have been fully decommissioned.

[b] n.a.: not applicable.

[c] In addition, thirteen have been fully decommissioned.

Following its use in a reactor, spent fuel is highly radioactive, emits significant radiation and heat, and is typically transferred to a fuel pool for several years. After this period (sometimes referred to as decay storage), spent fuel is safer and easier to handle and can be transferred to interim storage facilities. Spent fuel contains uranium, fission products, plutonium and other heavier elements. Some States reprocess spent fuel, resulting in the reuse of the uranium and plutonium in new fuel, as well as the separation of waste products.

During the operation of a reactor, different types of LLW and ILW are generated. This waste includes filters used in water and air treatment, worn out components and industrial waste that has become contaminated with radioactive substances. This waste has to be conditioned, packaged and stored prior to its disposal. Most of this waste (by volume) has low levels of radioactivity.

At the end of the operating life, a reactor is shut down and eventually dismantled. During dismantling, contaminated and activated components are separated, treated and if necessary managed as radioactive waste; the largest volumes generated are in the VLLW or LLW classes. Smaller volumes of ILW are also generated. The majority of the waste (by volume) from dismantling is, however, not radioactive and can be handled as industrial waste, in accordance to the State's regulations.

3.2. WASTE FROM NUCLEAR FUEL CYCLE FACILITIES

The cycle for producing and treating nuclear fuel includes the following:

- Uranium mining and milling (UMM);
- Conversion of uranium oxide to uranium hexafluoride and back;
- Enrichment;
- Fuel fabrication;
- Reactor operation;
- Spent fuel storage;
- Reprocessing and manufacturing of new fuel containing uranium or a uranium/plutonium mixed oxide (MOX).

Since the base material, uranium, is radioactive and new radioactive elements are formed during reactor operation, radioactive waste is generated in all steps of the nuclear fuel cycle. Most of this is VLLW, LLW or ILW and is treated in a similar way as the waste from reactor operation. The exceptions are waste from mining and milling, which is described in Section 3.3, and spent fuel and waste from reprocessing, which is described in Section 5.1.

During reprocessing, fission products, minor actinides, the metallic structure of the fuel and some process waste from the reprocessing process are managed as radioactive waste, along with operational waste similar to the waste from reactor operation (see Section 3.1). Decommissioning waste is also generated at the end of the operating life of a fuel cycle facility.

3.3. WASTE FROM URANIUM MINING AND MILLING AND OTHER MINING AND EXTRACTING ACTIVITIES

Some UMM operations generate large volumes of waste, such as waste rock and mill tailings. The waste rock is both the overburden rock, which only contains very low levels of NORM, and the rock from which the uranium bearing material has been separated, which contains residual uranium and other NORM. The mill tailing is the residue after the uranium has been extracted from the uranium bearing material to produce yellow cake. Further processing creates other wastes. Table 2 provides an overview of uranium production worldwide in 2012.

TABLE 2. URANIUM PRODUCTION WORLDWIDE, 2012 [14]

	UF_6 conversion facilities
Australia	No
Brazil	No
Canada	Yes
China	Yes
Czech Republic	No
France*	Yes
Germany*	No
Hungary*	No
India	No
Iran, Islamic Republic of	No
Kazakhstan	Yes
Malawi	No
Namibia	No
Niger	No
Romania	No
Russian Federation	Yes
South Africa	No
Ukraine	No
United States of America	Yes
Uzbekistan	No

* Production from mine rehabilitation only.

Waste rock and mill tailings are normally managed and disposed of close to the uranium mine or the uranium mill. The waste rock and tailings are not packaged and contained, but rather they are placed in nearby locations with suitable barriers to minimize their radiological and non-radiological impact on the surrounding environment. In some countries, UMM tailings and in situ leaching waste are not classified as radioactive waste. Hence, some States do not report the waste as radioactive waste, while others do. The presentation of data for this waste stream reflects these differences. Uranium extraction by the in situ leaching method usually also generates smaller volumes of radioactive waste and different waste forms.

Radioactive residues are also generated from oil and gas industries (e.g. scales and sludges), mining of other minerals and products (e.g. residues from extraction of thorium and rare earth elements), and the treatment and usage of drinking and process water. This waste type is not discussed in this publication, although some States have reported NORM waste in the National Profiles; UMM waste is presented separately in Section 6.

3.4. RADIOACTIVE WASTE FROM RESEARCH, AND MEDICAL AND INDUSTRIAL USE

Research using radioactive materials is conducted in many countries. The activities in which radioactive waste is generated include research involving reactors and fuel cycle facilities, and the use of radioisotopes as tracers or for the irradiation of materials. Generally, the same types of treatment and handling and disposal methods are applied as for the similar classes of waste resulting from nuclear power generation.

Sealed radioactive sources are widely used in research, trade, industry, medicine and agriculture. The most common fields of application for radioactive sources in industry include the calibration of measuring devices, materials testing, irradiation and sterilization of products, and level and density measurements. In medicine, radioactive sources are mostly used for radiotherapy and for irradiation of blood. The working lives of the sources used vary considerably, on account of the wide range in the half-lives of the radionuclides used. In most countries, devices operated on the basis of a licence for handling are returned to the equipment manufacturer by the operator after end of use, together with the source remaining in the device. The source manufacturer might check further use of the sources and reuse parts of them. Sources that cannot be reused have to be disposed of as radioactive waste.

3.5. RADIOACTIVE WASTE FROM MILITARY AND DEFENCE PROGRAMMES

Military and defence activities involving nuclear material create radioactive waste in various forms and in some cases account for the majority of waste produced in the country. Neither the Joint Convention [5] nor the Euratom Waste Directive [6] requires States to report this waste. However, some States have included military and defence waste in their Joint Convention reports. The aggregated tabulations in Section 6 include any waste being managed as part of the national inventory of radioactive waste.

3.6. OTHER POTENTIAL SOURCES OF RADIOACTIVE WASTE

In some countries, contaminated land or facilities have resulted from earlier industrial and nuclear operations and accidents. If such land is remediated or the facilities are refurbished or dismantled, radioactive waste is generated and has to be managed appropriately. International guidance on this is contained in IAEA Safety Standards Series No. WS-G-5.1, Release of Sites from Regulatory Control on Termination of Practices [15]. The expected waste arisings from such activities are not included in this publication unless they have been specifically included in national inventories or forecasts of radioactive waste.

4. FRAMEWORKS FOR THE MANAGEMENT OF SPENT FUEL AND RADIOACTIVE WASTE

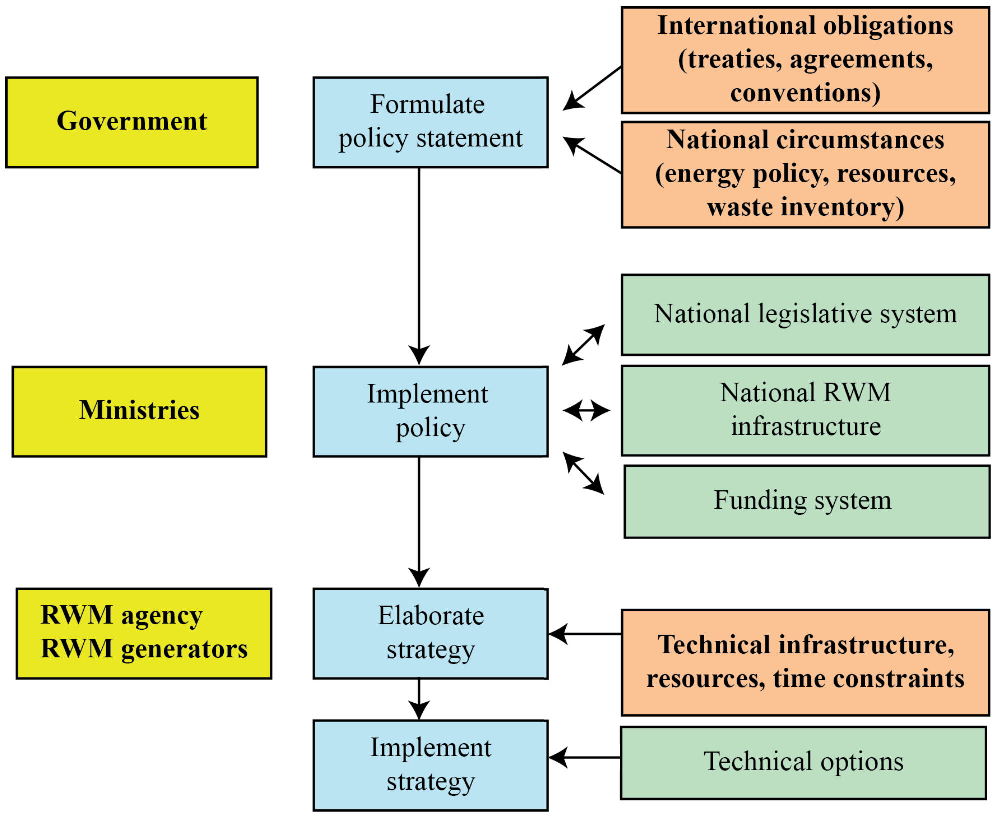
4.1. NATIONAL POLICIES

While the national arrangements for ensuring that spent fuel and radioactive waste are safely managed vary from country to country, there are some common features. The national legislative assembly is usually responsible for approving legislation to cover the safe management of spent fuel and radioactive waste. This legislation generally includes the establishment of a regulatory body and also, in many cases, an implementing body for spent fuel and radioactive waste management as well as defining the essential elements of the national policy for the management of spent fuel and radioactive waste and other related governance. Alternatively, national policy can be set out separately by governmental decree or ministerial directives. National policy typically addresses the following:

(a) Responsibilities within the country for spent fuel and radioactive waste management;
(b) Arrangements for financing the management (including disposal and decommissioning);
(c) Preferred management options for spent fuel, policies for waste disposal, import and export of spent fuel and radioactive waste;
(d) Decommissioning of nuclear facilities;
(e) Public information and public involvement in related decisions.

To implement the national policy, one or several strategies have to be developed, which is generally the responsibility of the implementer of waste management practices, for example a national radioactive waste management organization (WMO) (see Section 4.4). Figure 5 indicates how policy and strategy might be developed.

In general, national policy on spent fuel and radioactive waste disposal is that it should be disposed of in the country where it is generated. For the specific case of spent fuel being transferred for processing in another country, the residual waste is generally returned to the originating country for long term management. This is a legal requirement for EU Member States, in line with Article 2(3)b of the Euratom Waste Directive [6]. Some countries are seeking joint (or multilateral) solutions for the management of spent fuel and radioactive waste, including disposal in facilities that are operated jointly by, or on behalf of, several States.[4] No such disposal facility is currently under development.



Source: Figure 1 of Ref. [16].

FIG. 5. The principal steps in the development and implementation of a radioactive waste management (RWM) policy and strategy.

[4] The option of sharing of disposal facilities is recognized in Recital 33 of the Euratom Waste Directive [6]: "Some Member States consider that the sharing of facilities for spent fuel and radioactive waste management, including disposal facilities, is a potentially beneficial, safe and cost-effective option when based on an agreement between the Member States concerned."

The export and import of spent fuel and radioactive waste is subject to strict controls. Many States prohibit the import of spent fuel and radioactive waste. Other States, such as France, the Russian Federation and the United Kingdom, allow the import of spent fuel from other countries for reprocessing, usually returning reprocessed materials and any waste as byproduct to the country of origin. Several States have returned spent fuel from research and other non-power reactors for reprocessing and disposal, for example to the Russian Federation and the United States of America.

States which are suppliers of sealed radioactive sources for use in medicine and industry, for example Canada, France, Germany, the Russian Federation, South Africa and the United States of America, also accept the return of disused sealed radioactive sources (DSRSs).

4.2. NATIONAL STRATEGIES

Most countries have national strategies for implementing radioactive waste management, and include, for example, plans for implementing national policy, the development of the requisite facilities, the identification of roles and the setting of targets. It is evident from the National Profiles on the CD-ROM accompanying this publication that some States have well developed strategies and plans to manage all types of waste, from its creation until its final disposal and a few have implemented almost all of the planned steps (e.g. Finland, France and Sweden). In other countries, less progress has been made in national management plans, particularly for spent fuel and HLW. The slow pace associated with moving towards final disposal in many countries is dominated by the time taken to gain public acceptance of proposals to site facilities in specific areas, and the very significant costs associated with development of geological disposal facilities. For these reasons, some States with small nuclear programmes have not yet established their preferred national approaches, especially for the long term management of spent fuel and HLW.

The Euratom Waste Directive [6] requires that each EU Member State prepare a strategy expressed as a national programme for managing and disposing of all kinds of waste. The programme is to describe the facilities needed and all activities connected to their implementation (e.g. R&D and public involvement). Submission to the European Commission of the first reports on the national programmes was required by August 2015. Revised programmes are to be reported whenever substantial changes are introduced. An overview of national strategies for spent fuel and different types of radioactive waste is provided in Section 5.

4.3. LEGAL FRAMEWORK

National laws and regulations provide the legal framework for ensuring that radioactive waste is managed in a safe and appropriate manner. The legal framework also provides the legal basis for ensuring sufficient and timely funding of spent fuel and radioactive waste management activities — including the provision of disposal facilities and establishing requirements for public involvement in the decision making process. While legal instruments vary, they typically assign roles and responsibilities for nuclear activities, including radioactive waste management, to operating organizations, ministries and other governmental organizations. Requirement 2 of IAEA Safety Standards Series No. GSR Part 1 (Rev. 1), Governmental, Legal and Regulatory Framework for Safety [17], states that:

> **“Requirement 2: Establishment of a framework for safety**
>
> **“The government shall establish and maintain an appropriate governmental, legal and regulatory framework for safety within which responsibilities are clearly allocated.”**

More specifically for the safe management of spent fuel and radioactive waste, Article 19(2) of the Joint Convention [5] states that:

“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."

Similar requirements are given in the Euratom Waste Directive [6]. The National Profiles on the CD-ROM accompanying this publication provide information on the national legal frameworks in each of the countries.

4.4. REGULATORY FRAMEWORK, ROLE AND RESPONSIBILITIES

Requirements 3 and 4 of GSR Part 1 (Rev. 1) [17] establish the essential elements of a regulatory framework:

"Requirement 3: Establishment of a regulatory body

"The government, through the legal system, shall establish and maintain a regulatory body, and shall confer on it the legal authority and provide it with the competence and the resources necessary to fulfil its statutory obligation for the regulatory control of facilities and activities."

"Requirement 4: Independence of the regulatory body

"The government shall ensure that the regulatory body is effectively independent in its safety related decision making and that it has functional separation from entities having responsibilities or interests that could unduly influence its decision making."

At the government level, the ministries or departments of energy, industry, economy and development, with responsibilities for ensuring adequate energy supplies, have an interest in spent fuel and radioactive waste management, and often support the nuclear power industry in making arrangements for managing spent fuel and radioactive waste. The ministries responsible for ensuring that public health and the environment are adequately protected are typically responsible for regulating, governing and managing any hazards presented by spent fuel and radioactive waste.

The ultimate role of the regulator is to provide adequate oversight to ensure that nuclear activities are performed in a safe manner and in accordance with existing laws and regulations. Regulators are usually responsible for establishing regulations and guidance appropriate for ensuring the safety of radioactive waste management and for supervising, monitoring and enforcing the regulations. The independence of the regulatory body is important, and it is also emphasized in Article 20(2) of the Joint Convention [5]. An evident challenge is to ensure the independence of the regulator, for example, where the government ministries or departments concerned with energy production are not sufficiently separated from those concerned with health and safety. For most OECD/NEA members, nuclear safety regulators are now clearly separated from the national ministry in charge of energy or industry [18]. Specific information on national regulatory bodies is given in the National Profiles on the CD-ROM accompanying this publication.

The basic responsibilities for ensuring the safety of spent fuel and radioactive waste management are assigned by all States involved in this study in accordance with the above norms, although in different ways — the differences are usually due to variations in national legislative and regulatory systems. In some countries, for example, the owner or licence holder of a spent fuel and radioactive waste management facility is a private entity and thus is responsible for ensuring safety. In other countries, the owner or licence holder might not be completely distinct from the government and so the responsibility for ensuring the safety of spent fuel and radioactive waste management essentially rests with the State.

While it is made clear in the Fundamental Safety Principles [9], the Joint Convention [5] and the Euratom Waste Directive [6] that the prime responsibility for ensuring the safety of spent fuel and radioactive waste management rests with the licence holder (usually the owner of the facility), it is also evident that ultimate responsibility for ensuring that programmes are prepared for disposal of radioactive waste rests with the State in which that waste is generated. These obligations are implemented in each State through legislation and regulations in which the roles and responsibilities of the relevant organizations are established.

In some countries, the generators of spent fuel and radioactive waste are responsible for all activities for the safe management, including disposal of spent fuel and radioactive waste. This is true for the management of waste from nuclear power plants in Canada, Finland, Japan and Sweden. In other countries, however, the State has created a separate organization responsible for disposal, while the responsibility for the waste management of spent fuel and radioactive waste remains with the waste producer. Such an approach is used for managing all radioactive waste in China, France, Germany, the Russian Federation and Switzerland and for spent fuel in the United States of America.

4.5. WASTE MANAGEMENT ORGANIZATIONS

Even though the primary responsibility for managing spent fuel and radioactive waste rests with the owner or licence holder of a facility, there is a practical need for arrangements at the national level due to the longer term aspects. Many States have created national radioactive WMOs that are responsible for developing arrangements for disposal of spent fuel and radioactive waste. These WMOs may also be responsible for waste processing and interim storage and for the centralized collection and management of spent fuel and radioactive waste. The European Commission [2] finds that:

> "In some Member States without nuclear power programmes, the quantity of waste concerned might not justify the existence of a dedicated WMO. In these cases responsibility for such matters can be taken by a national research centre (eg. Austria, Greece), by a Ministerial department (eg. Luxembourg) or other body….
>
> "Already among the Member States having a nuclear power program, it would seem that there is no single model for a successful WMO. The role of such organisations varies widely between Member States from those concentrating mainly on repository development and operation e.g. ANDRA in France, to those which have also responsibility for all historic liabilities including site operation, such as in the UK (NDA). Additionally the status varies from that of a public utility to a subsidiary of commercial NPP operators, as in Sweden (SKB) and Finland (Posiva). The main requirement would seem to be that responsibilities are clearly laid down in the national framework and that there are adequate financial arrangements."

The nature and role of WMOs in States that provided a National Profile for this publication is given in Table A–2.

4.6. FUNDING ARRANGEMENTS

In most countries, waste producers are responsible for the financing of all activities connected to the management and disposal of spent fuel (if it is regarded as waste) and radioactive waste and for the decommissioning of the facilities. Part of the reason for establishing funds is that if the radioactive waste is generated through the operation of nuclear power plants or from the decommissioning, the costs should be seen as an operational cost, and the funds for waste management should be collected while the nuclear power plants are productive and earning money. Funding systems based on the 'polluter pays' principle have been widely adopted. Many of these costs appear long after the nuclear power plants have ceased to operate and at a time when funds are no longer being created from electricity production. It is therefore necessary to make arrangements to ensure long term funding. For this purpose, a special fund has been established in many countries to cover the costs of spent fuel and radioactive waste management and disposal. In some countries (e.g. Finland and Sweden), this fund should also cover the costs for decommissioning the facilities and managing the waste from decommissioning. In other countries (e.g. Switzerland and the United States of America), separate funds have been established for decommissioning.

France, the Russian Federation, Ukraine, the United Kingdom and the United States of America also have a long term waste legacy, dating from earlier nuclear activities: the State retains the responsibility for the management of waste from these activities. In most cases, no segregated funding arrangement has been established. Instead, the funding for current and future waste management is, and will be, met directly from government sources. This is often the case for managing and disposing spent fuel and radioactive waste from nuclear research centres, mostly owned by the State. Table A–3 on the CD-ROM accompanying this publication summarizes the funding arrangements for spent fuel and radioactive waste management in some countries, based on the publicly available information.

Table A–3 shows that funding arrangements can include the costs for management and disposal of all the radioactive waste being generated in a country, while in other cases the funding is limited to the disposal of spent fuel or HLW and the decommissioning of nuclear facilities (i.e. activities that normally occur long after power production ends). In the latter, the costs of management and disposal of other types of waste are paid directly by the waste producers as an operating expense. The funding arrangements described in Table A–3 mainly relate to spent fuel and radioactive waste from nuclear power plants. In some countries (e.g. Sweden), similar arrangements have been implemented for small producers of radioactive waste (i.e. the waste producers pay for waste management and disposal). In other countries, the State takes responsibility for these costs in return for fees paid by the waste producers.

5. SPENT FUEL AND RADIOACTIVE WASTE MANAGEMENT PROGRAMMES: CURRENT PRACTICES AND TECHNOLOGIES

In most countries, waste classification schemes have existed for many years and can be defined within the legal framework as laws and regulations promulgated by the regulatory body. Classification of waste in some instances relates to predisposal activities, for example the radiation protection of workers. In other cases, it is tied to the most appropriate management strategies for the disposition of the waste streams. Significant differences exist between the various national schemes. In order to unify and develop a common framework in which the discussion of waste management can be conducted between countries, various international classification schemes for radioactive waste have been developed over the years. This publication follows the definitions in para. 2.2 of GSG-1 [1] (see Section 3).

This publication does not focus on EW or on VSLW as defined by GSG-1 [1], although there are differences between how States regard clearance and exemption. For example, the concept of clearance in France is not used: any material from an area where nuclear activities (as defined in the regulations) are undertaken is considered to be radioactive, and the waste is managed by means of a specific treatment or disposal in dedicated facilities. In Germany, emphasis is placed on the recycling of materials after use and the application of the concepts of EW and clearance of materials for reuse. Thus, waste that in some countries is considered to be EW is regarded as VLLW or LLW in other countries and can have an influence on the volumes reported.

While GSG-1 [1] largely defines waste classification based on the disposal strategy necessary to provide long term safety, precise boundaries between classes (e.g. in terms of specific activity) are not specified, as this depends on the safety case for a specific facility. Hence, precise interpretation of the waste classes will vary between countries, for example the radiological criteria for waste acceptance of LLW at near surface repositories will be based on the specific safety case for that facility. The clearest differences can be found in the interpretation of ILW by some States, reflecting the range of disposal options being considered for this class. Some States classify short lived waste with a high content of radioactivity as ILW in their national schemes, even though this can be disposed of in a similar way as LLW, subject to the safety case for the specific disposal facility. Such waste is classified as LLW in accordance with the classification of radioactive waste in GSG-1 [1]. Furthermore, there may be national requirements that waste containing long lived components be emplaced in geological disposal facilities, although this waste could be classified as LLW or ILW according to the classification in GSG-1 [1], depending on the actual long lived radionuclides present.

Several national classification systems were introduced early, and they sometimes reflect the classification system recommended in the safety standard superseded by GSG-1 [1].[5] In some countries, the national classification system relates to the waste acceptance criteria for specific disposal facilities, rather than being based on a generally applicable system. In Australia, Georgia and the Republic of Korea, the classification in GSG-1 [1] has already been adopted or is expected shortly. Some States use radioactive waste classification based on other factors, such as the presence (or absence) of heat generation in Germany, disposal route in France and Sweden, and radioactivity level in the United States of America.

Radioactive waste is often present together with other hazardous materials and both will have to be considered when deciding on handling, treatment and disposal. In the United States of America, this waste is termed 'mixed waste'. It should be noted that in many instances the radioactivity might not be the most hazardous aspect of the waste.

In order to analyse global inventories and projections of waste, it is important to understand how States classify waste. Each National Profile further describes the waste classification used in the country and provides a suggested equivalence to the classification in GSG-1 [1]. This allows an approximate summation of the amounts of different types of waste. Section 6 provides additional discussion on this process. Table A–4 summarizes the waste classification schemes used in different countries, based on the responses to the National Profile questionnaires.

5.1. SPENT FUEL MANAGEMENT

Spent fuel is generated from the operation of all types of nuclear reactor. It is considered to be waste in some countries or a potential future energy resource in others. If it is considered waste, it will be disposed of as such after some decades of interim storage ('once through fuel cycle'). Otherwise, it might be reprocessed to recover fissile materials for future use ('closed fuel cycle').

A summary of the fuel cycle strategies adopted in different countries is given in Table A–5. The majority of States have adopted the policy of direct disposal of spent fuel, while several States with the largest nuclear programmes (France, China, Japan, the Russian Federation and the United Kingdom) have adopted the policy of reprocessing nuclear fuel and recycling the separated material. Germany and the United States of America have changed their policy from reprocessing and recycling to direct disposal and are currently planning spent fuel repositories.

5.1.1. Spent fuel reprocessing

Spent fuel undergoing reprocessing can be separated into three main components: uranium, plutonium, and waste containing fission and activation products. Uranium and plutonium can be reused as nuclear fuel for reactors, while the fission and activation products are waste products, which are vitrified and stored for further handling and disposal. Secondary waste from reprocessing and the metal components of the fuel are conditioned in a stable matrix for storage and ultimate disposal.

States which currently operate reprocessing facilities on a significant scale include France, India, Japan, the Russian Federation and the United Kingdom (see Fig. 6 and Table 3). In the past, reprocessing was also carried out by the United States of America. States such as Belgium, Bulgaria, the Czech Republic, Germany, Italy, Japan, the Netherlands, Slovakia, Spain, Sweden and Switzerland have been able to utilize these facilities for reprocessing fuel. The option of reprocessing abroad has also been utilized for some research reactor fuel (e.g. Australia, Belgium and Sweden). The practice for many research reactors has been to return the fuel to the producer, mainly to the Russian Federation and the United States of America. Since 2010, several States, including Australia, Bulgaria, Italy, Japan and the Netherlands, have continued to utilize this option; other States have adopted a policy of storing the fuel on their own territories.

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of Radioactive Waste, Safety Series No. 111-G-1.1, IAEA, Vienna (1994).

FIG. 6. AREVA reprocessing plant, France (courtesy of AREVA).

TABLE 3. COMMERCIAL SCALE REPROCESSING FACILITIES

	Facility	Capacity (t HM/a)	Status
France	UP2-400, La Hague	400	Under decommissioning
	UP2-800, La Hague	800	In operation
	UP3, La Hague	800	In operation
	UP1, Marcoule	600	Under decommissioning
Japan	Rokkasho	800	In commissioning
Russian Federation	RT-1, Mayak	400	In operation
	RT-2, Zheleznogorsk	60	Under construction
United Kingdom	NDA THORP, Sellafield	900	In operation
	NDA Magnox Reprocessing	1500	In operation

Source: IAEA Integrated Nuclear Fuel Cycle Information System.

Spent fuel reprocessing abroad is subject to strict controls and is performed on the basis of bilateral agreements. HLW from spent fuel reprocessing (as well as other waste classes) is typically conditioned by the reprocessor and, in most cases, the contracts for reprocessing abroad envisage the return of the products and the conditioned waste to the country where the fuel was originally used. Some early contracts provided for the waste to remain in the country where the fuel was reprocessed. This option is currently available only in very limited cases.

5.1.2. Uranium and plutonium reuse

The uranium separated during reprocessing can be reused as fuel in present day reactors following conversion and, if necessary, enrichment. The plutonium can be made into MOX fuel, in which uranium and plutonium oxides are combined. MOX fuel is currently used in light water reactors. In the longer term, the plutonium is planned to be used in fuel for Generation IV[6] reactors, where the energy value of the uranium and plutonium can be better utilized. Several States considering reprocessing have plans at different stages of development for future fast reactors. By the end of 2016, however, only the Russian Federation was operating fast reactors (e.g. the BN-600). The Russian Federation has utilized its MOX plants to produce fast breeder reactor fuel. MOX plants are also planned to begin operation in the next few years in the United States of America (i.e. the Mixed Oxide Fuel Fabrication Facility, MFFF) and in Japan. At present, only France has a commercial MOX fuel fabrication facility in operation. This facility, MELOX, also provides services to several other States. The United Kingdom also operated a MOX facility, but this ceased operation in 2011.

5.1.3. Transport of spent fuel

The management of spent fuel involves a number of transport steps between nuclear power plants, storage facilities and reprocessing facilities, as well as eventually to disposal facilities. Transport is typically undertaken in specially designed transport containers that provide security, shield workers and the general public, and cool the fuel. These transport operations are strictly controlled according to national regulations, which are often based on the transport regulations in IAEA Safety Standards Series No. SSR-6, Regulations for the Safe Transport of Radioactive Material (2012 Edition) [19]. Most transport operations are performed within one country, but some journeys cross national frontiers. Each State involved in a transboundary movement has to take the appropriate steps to ensure that the transport operation is undertaken in an appropriate manner and with the authorization of the countries of origin, destination and transit.

For States that require spent fuel reprocessing but do not have reprocessing facilities of their own, such transboundary movements are necessary. Similarly, the transboundary transport of spent fuel is necessary for States sending spent fuel from research reactors and other reactors back to the country of origin. In the case of an open cycle, the transport will be when spent fuel is conditioned and packaged and then sent to final disposal.

5.1.4. Storage

Whatever management option is chosen, storage of spent fuel will be required for some period of time. The storage time will depend on the management strategy adopted, from a few months to several decades or longer. Storage options include wet storage in storage pools or dry storage in storage casks or vaults. Almost all nuclear power reactors have some form of spent fuel storage pools. They were included as a necessary component in the original design of the reactors. Additional storage capacity, wet or dry, can be built to extend the capacity of nuclear power reactor spent fuel storage. In most cases, the new stores have been built at the reactor site in close proximity to the reactor. Such stores together with the original storage pools are called at-reactor (AR) stores.

However, due to the limited capacity at some reactor sites, the development of storage capacity away-from-reactor (AFR) has been necessary. Access to an AFR site requires transport over public roads, railways and sea lanes. Typically, AFR facilities are purposely built, under a separate licence, for spent fuel storage located away from the main reactor buildings. The storage method for new AR and AFR stores was initially wet storage (see Fig. 7), but dry storage techniques of different types have been developed (see Fig. 8) and are now widely adopted (see Table A–6). Reprocessing facilities are normally equipped with large pools at the reception for buffer storage before reprocessing.

[6] Generation IV nuclear energy systems are next generation technologies being developed to have comparative advantages, including reduced capital cost, enhanced nuclear safety, minimal generation of nuclear waste and further reduction of the proliferation risk of weapon usable materials.

FIG. 7. The interim storage of spent fuel at Clab, Sweden (courtesy of SKB).

FIG. 8. Concrete casks storing spent fuel at the Connecticut Yankee nuclear power plant site (courtesy of NAC International).

5.1.5. Disposal of SNF

For the open fuel cycle, spent nuclear fuel will be handled in a very similar way to HLW. After several decades of interim storage and packaging (see Fig. 9), it will be disposed of in a deep geological repository (see Section 5.5.3 for further details).

FIG. 9. Spent fuel disposal canisters, Posiva, Finland (courtesy of Posiva).

5.2. VERY LOW LEVEL WASTE

VLLW often exists in large volumes, and it is mainly generated during the decommissioning of a nuclear facility or from the cleanup of contaminated sites. Typical VLLW includes concrete, soil and rubble. This class is currently recognized as a distinct classification by only a small number of States (e.g. France, Japan, Lithuania, Spain and Sweden). In most other country classification systems, it is included as part of the LLW stream.

5.2.1. Processing

The volume of potential VLLW can be reduced by appropriate characterization to separate those components that can be released from regulatory control as cleared waste (in countries where this concept is used). VLLW is typically not subject to further processing, apart from its packaging, due to the very large quantities involved and the low content of radionuclides.

5.2.2. Storage

Generally, VLLW is stored at the site of its generation or in a centralized storage facility until it is transported to a suitable disposal facility. During this stage, a simple shelter or temporary cover might be sufficient to provide protection from atmospheric influences (precipitation and wind).

5.2.3. Disposal

In France and Spain, VLLW is disposed of in purpose built disposal facilities in shallow trenches with engineered covers, often near the site of generation to avoid the transport of large volumes of material (see Fig. 10). In other countries, it is disposed of together with other waste types (e.g. LLW). The decision on disposal method is usually made on economic and regulatory grounds.

FIG. 10. Very low level waste disposal at the Cires facility, France (courtesy of ANDRA).

5.3. LOW LEVEL WASTE

LLW generally does not require significant shielding during handling and interim storage. Taken together, VLLW and LLW typically account for more than 95% of the volume but less than 2% of the radioactivity of all radioactive waste. LLW is generally conditioned into a solid form and placed into concrete or steel packages, which provide containment and shielding.

5.3.1. Processing

The treatment and conditioning of LLW either takes place at the facilities where it is generated or at a purpose built centralized facility. The waste is segregated, treated, conditioned, packaged, monitored and stored, as appropriate, before being transferred to the disposal facilities. Drying, incineration, evaporation, high pressure compaction, melting and cementing are common processes applied to the conditioning of LLW (see Fig. 11 for an example of compaction). Concrete containers, steel drums and steel boxes are commonly used for waste packaging. Subject to meeting all relevant safety requirements, their dimensions are selected to fit the dimensions and shapes of disposal spaces and transport packages.

5.3.2. Storage

In most cases, LLW is stored at the site of origin until further processing. After processing, storage is often necessary if suitable disposal facilities are not available. Interim storage for periods of up to 100 years or longer can be considered as an option provided that the waste containers remain intact and are not subject to degradation. Such long term interim storage is being implemented in the Netherlands (see Fig. 12).

5.3.3. Disposal

LLW, most of which has a half-life less than 30 years, is disposed of in near surface repositories in many countries (see Table A–7 and Figs 13–15). These are trenches or concrete vaults into which containerized waste is placed. An engineered cover system is placed over the waste to limit water infiltration and surface erosion, and to prevent intrusion by burrowing animals. While disposal of LLW in a near surface facility is a typical strategy for many of the States that responded, some (e.g. Finland, Germany and Switzerland) have chosen, or are considering, the option of disposing LLW in repositories at depths between 50 m and 1000 m. The facilities are subject to surveillance until the hazard associated with the waste has declined to acceptable levels (typically a few hundred years).

FIG. 11. Waste compaction (courtesy of TVO).

FIG. 12. Long term interim storage in the Netherlands (courtesy of COVRA).

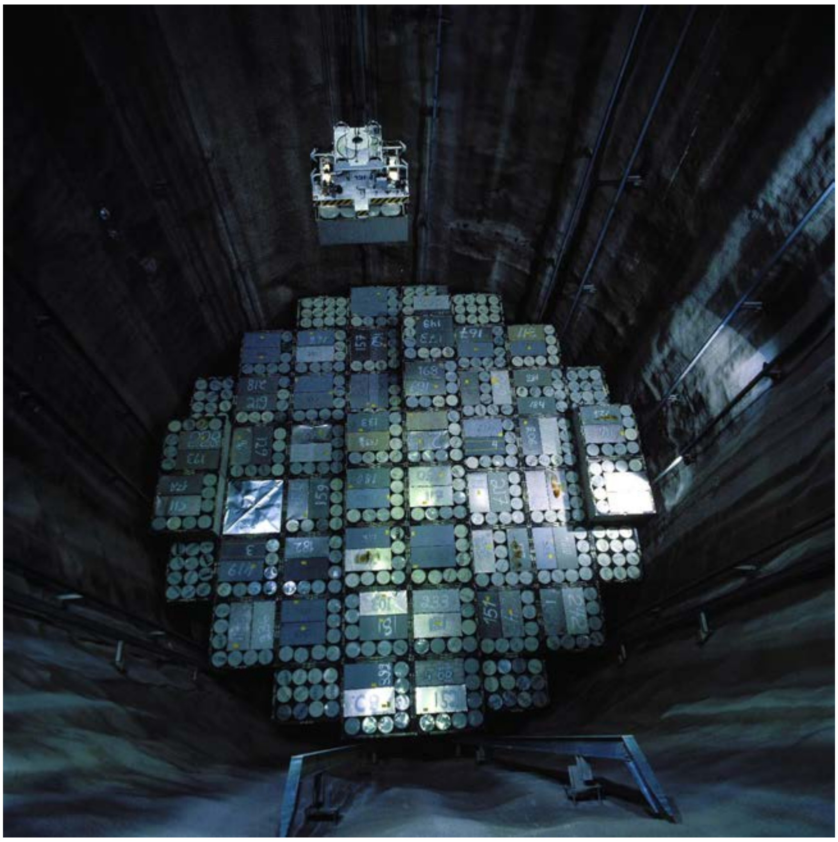


FIG. 13. Low level waste disposal facility in Olkiluoto, Finland (courtesy of TVO).

FIG. 14. Low level waste disposal facility in El Cabril, Spain (courtesy of Enresa).

FIG. 15. Low and intermediate level radioactive waste disposal vault in Bataapati, Hungary (courtesy of PURAM).

Some States dispose of LLW in subsurface facilities, and a small number are considering its co-location in geological facilities with ILW, HLW or spent fuel. Co-disposal can result in a simpler waste management system because fewer facilities need to be developed. However, co-location can also introduce design complexity to avoid interferences between the waste types (e.g. decomposition of LLW can result in the generation of complexing agents that reduce the safety of higher level wastes), as well as significant increases in the volume of material requiring handling at geological depths.

5.4. INTERMEDIATE LEVEL WASTE

ILW generally contains significant amounts of long lived radionuclides and therefore requires disposal at depths that provide isolation from the biosphere over the long term. ILW requires shielding during handling and interim storage and can account for 3–5% of the radioactivity of all radioactive waste.

5.4.1. Processing

The processing of ILW either takes place at the facilities where it is generated or at a purpose built centralized facility. Processing consists of collection, segregation, decontamination, volume or size reduction, and stabilization prior to packaging. Drying, evaporation, high pressure compaction, melting and cementing are common technologies applied in the treatment and conditioning of ILW. Care needs be taken during treatment not to increase radioactivity concentrations beyond the capability of the treatment facilities or packaging to handle the resulting radiation levels and the extent of heat emission.

Depending on its intended storage or disposal destination, ILW is often treated and conditioned by incorporating it into a matrix (e.g. cement or bitumen) and then using suitable container materials to provide the required radiation shielding. In some cases, where additional matrices are not required to ensure safety, conditioning is limited to packaging. In other cases, the waste object itself (such as a large vessel with internal contamination) forms the container if it can be suitably sealed.

Concrete containers with steel reinforcement, steel drums and steel boxes are commonly used for waste packaging. Their dimensions are selected to meet safety requirements and to be compatible with the dimensions of transport casks and of disposal vaults. ILW containers can either be self-shielded or rely on external shielding to provide the necessary radiation protection. Both design concepts are used extensively.

5.4.2. Storage

Options for storage of ILW are broadly similar to those for LLW except that greater attention needs to be given to the provision of adequate containment and shielding (see Fig. 16).

FIG. 16. Intermediate level waste storage at Trawsfynydd nuclear power plant, United Kingdom (courtesy of Nuclear Decommissioning Authority).

5.4.3. Disposal

The only licensed disposal facility for long lived ILW[7] is the Waste Isolation Pilot Plant (WIPP), United States of America, where long lived, non-heat-generating waste from defence activities is disposed of in a geological repository built in salt beds. The Republic of Korea and Sweden have both licensed and operated geological disposal facilities for short lived ILW (e.g. Gyeongju facility, in the Republic of Korea; and SFR, Final Repository for Short-lived Radioactive Waste, in Sweden). Elsewhere, ILW is held in storage until a disposal facility suitable for this material becomes available. Germany and Switzerland envisage that all LLW and ILW will be disposed of in one multipurpose, deep geological facility, obviating the need to separate waste containing short and long

[7] Note that the definition of ILW used in GSG-1 [1] and throughout this publication includes all forms of ILW that require a greater degree of containment and isolation than near surface disposal can provide.

lived radionuclides before disposal. Germany plans to dispose of all types of radioactive waste in deep geological formations, with waste being classified either as heat generating or non-heat generating, with separate repositories. In France, long lived ILW will be disposed together with HLW in the planned facility Cigéo (Centre industriel de stockage géologique, industrial centre for geological disposal).

5.5. HIGH LEVEL WASTE

HLW from reprocessing is typically vitrified and then stored for some decades to allow levels of heat generation to be reduced, in a similar way as for spent fuel. Following storage, spent fuel and HLW is to be disposed of in a deep geological repository at depths of several hundred metres or more in a suitable geological formation. Different types of geological media and associated engineered barriers are considered. Spent fuel disposal designs typically involve encapsulation in robust, corrosion resistant canisters awaiting disposal.

5.5.1. Conditioning

During conventional aqueous (PUREX type — plutonium and uranium recovery by extraction) reprocessing, HLW is converted to a liquid form, which can subsequently be conditioned to produce a chemically durable and heat and radiation resistant solid matrix. Several types of glass (e.g. borosilicate and phosphate), and some ceramics, are used for the treatment and conditioning of HLW. All of the waste forms are based on the use of high temperature technologies, and the glass is discharged into containers which can also be used for storage. The vitrification process and all container handling operations are performed remotely in shielded cells. Significant experience has been obtained with the vitrification process in Belgium, France, Japan, the Russian Federation, the United Kingdom and the United States of America.

Some States include fuel cladding and structural material which was separated during reprocessing within the HLW class. However, it should be noted that this waste is generally not significantly heat emitting, and therefore could be considered as ILW according to the classification in GSG-1 [1].

5.5.2. Storage

HLW canisters are stored in air cooled vaults or casks similar to those used for spent fuel storage. Each reprocessing plant has large vaults for storage — mainly for their national HLW. States that have spent fuel reprocessed abroad, such as Belgium, Germany, Japan, the Netherlands, Switzerland and Ukraine, are typically required to take back the residual HLW for storage and ultimate disposal. In Germany and Switzerland, cask storage is used, while Belgium, Japan and the Netherlands use vault storage.

Non-processed liquid HLW (mainly from military programmes) exists in some countries, mainly the Russian Federation and the United States of America. It is stored in cooled tanks constructed of steel (usually corrosion resistant stainless steel alloys) awaiting conditioning. The tanks are normally located underground to provide radiation shielding.

5.5.3. Disposal

There is presently a broad consensus among technical experts that the preferred method of ensuring long term safety for HLW is isolation in a deep geological disposal facility. Geological disposal facilities for long lived waste, if properly sited and constructed, provide passive, multibarrier isolation of radioactive materials. Emplacement in carefully engineered structures buried deep within suitable rock formations provides the long term stability typical of a stable geological environment. At depths of several hundred metres, in a tectonically stable region, processes that could disrupt the disposal facility are so slow that the deep rock and groundwater system remain practically unchanged over hundreds of thousands or even millions of years [20]. States are studying different geological media, depending on availability, for their geological disposal facility. Before disposal, the spent fuel will be encapsulated in a corrosion resistant and mechanically stable container, which will provide isolation for thousands of years. The requirements on the container integrity depend on the repository concept and the geological medium chosen.

Currently, there are not any operating deep geological repositories for HLW, although research into this has been undertaken for several decades, using a range of underground research laboratories. Finland, France and Sweden are close to the construction and implementation of their own deep geological repository for HLW (see Figs 17 and 18). Finland and Sweden have submitted construction licence applications at selected sites in crystalline rock. They expect commissioning in the 2020s, and in Finland, the construction licence was granted in 2015.

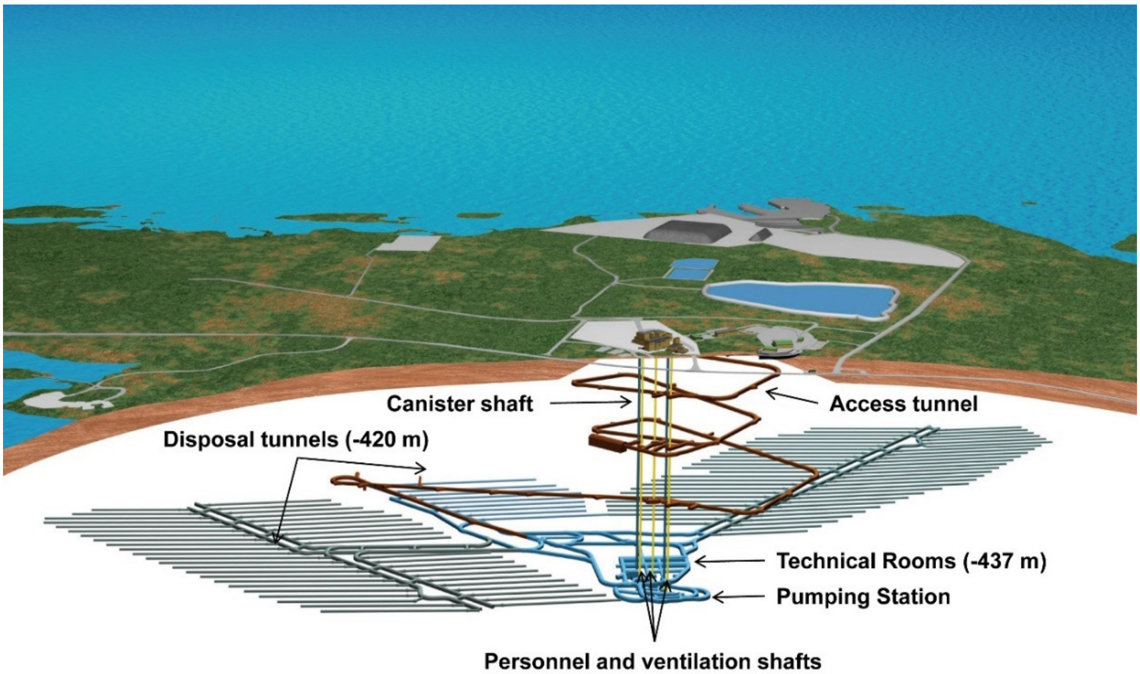


FIG. 17. The ONKALO underground research facility, Finland (courtesy of Posiva).

FIG. 18. Construction of the ONKALO underground research facility, Finland (courtesy of Posiva).

In the United States of America, a licence application was filed by the United States Department of Energy for a repository in tuff host rock, located at Yucca Mountain, Nevada. The application was submitted to the United States Nuclear Regulatory Commission (NRC) in June 2008, but funding for the project was withdrawn by the US Government in 2011 for 2012 and beyond. The NRC, however, finalized the review of the application and completed a safety evaluation report in January 2015. A final decision on Yucca Mountain is currently on hold.

Most other States with HLW are working towards national solutions, although they are mostly still at the planning stage. Some States have also indicated an interest in developing multinational disposal facilities. France has held the public debates on the geological disposal facility project Cigéo in clay host rock with positive results and has started to develop the design of a facility with an expected operational start in 2025. A licence application is planned to be submitted in 2017. Both HLW and ILW are to be disposed of in this repository. In Germany, many studies, including exploratory tunnels, have been made for the disposal of spent fuel and HLW in salt beds at Gorleben. This work was suspended and a new siting process was initiated in 2013. Other States are at an earlier phase of repository development. The current status of national radioactive waste disposal programmes is shown in Table A–7. The radioactive waste classifications used in Table A–7 are the national classifications as described in the individual National Profiles, which are on the CD-ROM accompanying this publication.

5.6. DISUSED SEALED RADIOACTIVE SOURCES MANAGEMENT

The IAEA Code of Conduct on the Safety and Security of Radioactive Sources (Code of Conduct) [21] defines a radioactive source as:

> "…radioactive material that is permanently sealed in a capsule or closely bonded, in a solid form and which is not exempt from regulatory control. It also means any radioactive material released if the radioactive source is leaking or broken, but does not mean material encapsulated for disposal, or nuclear material within the nuclear fuel cycles of research and power reactors."

Depending on the intended use, sealed radioactive sources include a wide variety of radionuclides and activity levels. They are used widely in medicine, industry and agriculture and, because of this, they are found in almost all countries. At some point, sealed sources have to be replaced, usually because their activity level has declined below which the source is no longer suitable for its intended purpose. They are then considered to be 'spent' or 'disused' sources. The Code of Conduct [21] and IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [22], categorize radioactive sources according to their potential to cause serious health effects (see Table 4).

TABLE 4. CATEGORIES OF SEALED RADIOACTIVE SOURCES [23]

Category	Risk in being close to an individual source	Examples of uses
1	Extremely dangerous to the person	Radioisotope thermoelectric generators Irradiators
2	Very dangerous to the person	Industrial gamma radiography sources High/medium dose rate brachytherapy sources
3	Dangerous to the person	Fixed industrial gauges Well logging gauges
4	Unlikely to be dangerous to the person	Bone densitometers Level gauges
5	Most unlikely to be dangerous to the person	Permanent implant sources Lightning conductors

As a result of the problems associated with disposing of DSRSs safely, especially in countries with little or no radioactive waste management infrastructure, current good practice is to return the sources to a manufacturer for refurbishment, recycling or disposal. Some States insist upon this as a condition of the import and sale of sealed sources within their territory. However, many older DSRSs cannot be returned to their manufacturer for various reasons, the main one being that the manufacturer might not be traceable or no longer exists. As a result, many countries have inventories of legacy DSRSs.

5.6.1. International standards and rules

On account of the special nature of DSRSs and their widespread use, specific international standards have been developed for their management, including:

- Code of Conduct [21];
- Council Directive 2003/122/Euratom of 22 December 2003 on the control of high-activity sealed radioactive sources and orphan sources [24] (repealed with effect from 6 February 2018 by Council Directive 2013/59/Euratom [8]);
- Council Regulation (Euratom) No. 1493/93 of 8 June 1993 on shipments of radioactive substances between Member States [25].

5.6.2. Storage and conditioning

States with nuclear power facilities are likely to have the capacity for long term storage or disposal of DSRSs together with other types of radioactive waste. For many small countries, however, storing or disposing of the sources safely and securely presents an ongoing challenge.

Sources with short half-lives (e.g. ^{192}Ir) can be stored until the radioactivity in the source decays to low enough levels to allow release from regulatory control (i.e. clearance); while others (e.g. ^{226}Ra, which until recently was widely used) remain potentially hazardous for tens of thousands of years. Where disposal options are not available, long term storage facilities are required for many types of DSRS. Effective management involves repackaging the source, checking the condition of the source or source container regularly, and providing appropriate security measures.

5.6.3. Return to supplier

The return of DSRSs to the supplier usually involves transboundary movement. Most States now require that regulatory approval be given before a radioactive source can be imported and that for all but the shortest lived sealed sources (whose radioactivity level will be negligible after a few years), the manufacturer or supplier should agree to take back the source at the end of its useful life for its intended purpose. Often the manufacturer or supplier can recover the residual radioactive material and refurbish the source for another purpose (see Table A–8 for an overview of the strategies used in DSRS management).

5.6.4. Disposal

Unless they can be repatriated or recycled, most States generally envisage the final disposal of DSRSs in licensed radioactive disposal facilities. While shorter lived DSRSs can be disposed of in surface facilities, long lived DSRSs require subsurface disposal. Some States, such as the United States of America, currently dispose of DSRSs along with other radioactive waste. In countries with nuclear power programmes, long lived DSRSs currently in storage might be disposed of in geological repositories. States without nuclear power programmes are investigating borehole disposal as a potential management option for long lived and high activity DSRSs (see Fig. 19).

Of particular concern in some countries are consumer products such as smoke detectors that contain small radioactive sources. These often end up in uncontrolled disposal, such as domestic waste landfills or unregulated dumps. While individually they pose minimal risk, large numbers disposed of at the same location can create a potential hazard.

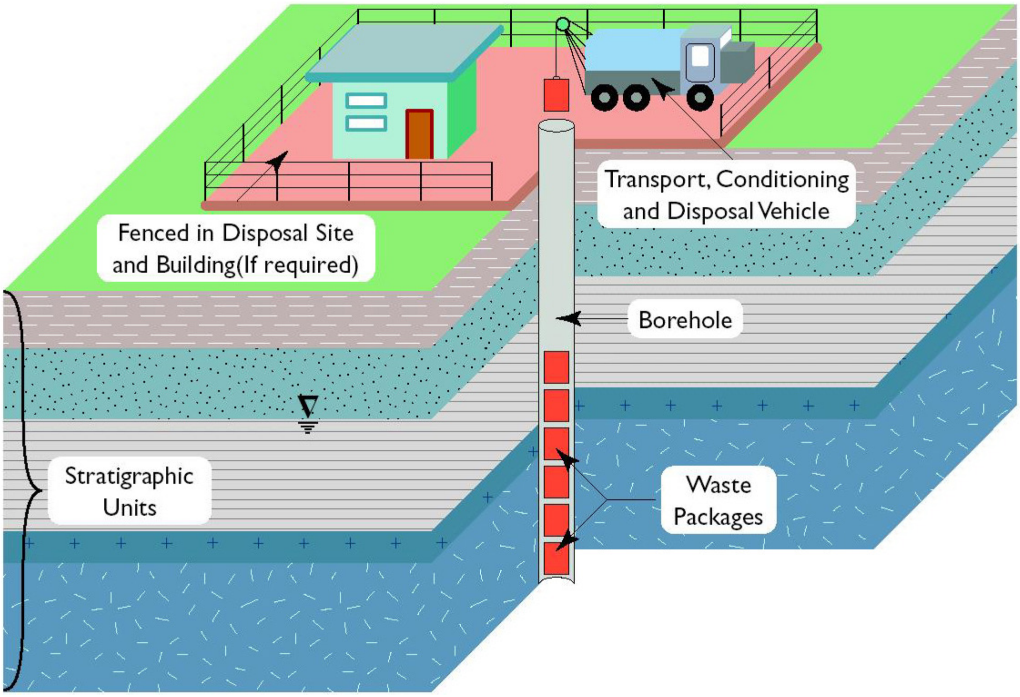


FIG. 19. Borehole disposal concept.

5.7. URANIUM MINING AND MILLING WASTE

Waste from extractive industries, including residues from uranium mining and contaminated soils have large volume and are typically disposed of in situ because it can be impractical to transport it elsewhere. The contaminated materials are placed in stable mounds with an appropriate cover system that provides isolation from the local environment.

6. INVENTORIES

6.1. DATA SOURCES

The main source of information used for inventories and forecasts is the National Profiles on the CD-ROM accompanying this publication. For States that did not submit a report, information about inventories is taken from the State's report to the Joint Convention, where this is publicly available.

6.1.1. National Profiles

A template for the National Profiles was generated to provide a structure for data collection that enabled aggregation of data at regional or global levels and to facilitate data analysis. The template includes tables for amounts of spent fuel and radioactive waste, together with transformation matrices to enable the transfer of the volumes given in national classification systems to the classification in GSG-1 [1]. A total of 47 States contributed National Profiles, which are provided on the CD-ROM.

Nuclear power plants generate significant quantities of spent fuel and radioactive waste and, accordingly, States without nuclear power plants generally have much smaller amounts of radioactive waste or spent fuel. The quality of the aggregated global quantities presented here is largely determined by the number of States with nuclear power plants that provided a National Profile. All countries have some radioactive waste, which in many cases is entirely comprised of DSRSs. All waste quantities provided in the National Profiles, no matter how small, have been included in the aggregated global data quantities presented here.

6.1.2. Joint Convention national reports

Joint Convention national reports are produced triennially, and Contracting Parties to the Joint Convention are encouraged to publish their national reports.[8] Data were used from this source for States that did not submit a national profile.

The Joint Convention national report includes a listing of spent fuel and radioactive waste management facilities in the State. It also provides inventories of spent fuel and radioactive waste in the States based on the national waste classification systems. Forecasts of spent fuel and waste storage and disposition are, however, not provided. National reports vary in the level of detail provided and in the measurement units used, requiring translation of waste quantities presented according to national classification into equivalent waste classification. The National Profiles and the Joint Convention national reports cover almost 95% of all nuclear power plants in the world. This provides a good basis for making regional and global aggregations of waste volumes. In this publication, information from States with significant inventories of radioactive waste is missing only for India and Pakistan.

6.1.3. Other sources

Other possible sources of information beyond those mentioned above were not used, with the exception of data on amounts of spent fuel that has been reprocessed in France, which was taken from industry estimations [26].

6.2. DESCRIPTION OF DATA COLLECTION

As noted previously, the precise definition of what constitutes radioactive waste and its classification into levels or categories varies widely among countries, which creates some inherent difficulties in aggregating inventory data. This section describes the approach taken to data collection and the model used to aggregate data from different countries on a common framework.

6.2.1. Conversion to IAEA waste classification

This publication uses the waste classification in GSG-1 [1] to present global values. This classification is based on the disposal route required to provide long term safety. However, some States intend to dispose of waste in facilities normally reserved for waste that presents a greater long term hazard (e.g. disposing of LLW in a geological repository). Furthermore, the boundaries between different classes are not defined by quantitative activity levels, but instead depend on the safety case for a specific facility. On that basis, waste of a particular class in one country might not have precisely the same level of activity as the same class of waste in another country — although the differences at the margins are typically not significant. To assist the conversion to the waste classification in GSG-1 [1], respondents were asked to include a conversion matrix as part of their National Profiles, indicating the proportions of waste from a national class corresponding to the appropriate waste classification in GSG-1 [1]. Estimates were made for States that did not provide a conversion matrix. A similar approach was used with data taken from the publicly available national reports under the Joint Convention [5].

6.2.2. Conversion to disposal volumes

Waste volumes can also be presented in different ways, for example corresponding to the current state of the waste, whether unprocessed or processed, or in the anticipated final volumes when the waste is ready for disposal. The template for the National Profiles requested waste volumes to be presented corresponding both to the current

[8] See www-ns.iaea.org/conventions/results-meetings.asp

state of the waste and its anticipated volume for disposal. To help minimize the inconsistency in volumes, this publication uses ‘as stored’ and ‘as disposed’ volumes. For some countries, with a known or assumed conditioning and disposal route, it is not problematic to transform the storage volume to the disposal volume. Estimations are, however, necessary to calculate the ‘as disposed’ volume, taking into account the repository requirements and the conditioning and packaging plan. For States without established plans for a repository and corresponding waste package geometries, several assumptions need to be made, for example concerning what further conditioning and packaging will be required for ‘disposal ready’ packages. In such situations, greater uncertainty exists concerning the disposal volumes. This uncertainty might increase if there is a possibility that conditioned waste packages are eventually placed in larger containers or overpacks for disposal.

6.2.3. Steps and uncertainties in determining global inventory

The data presented in the National Profiles have provided the basis for preparation of the global aggregated data presented in this publication. The determination of ‘as disposed’ waste volumes requires assumptions to be made concerning the waste processing and disposal strategies. This step tends to be particularly complex in the case of liquid waste, which inevitably involves the use of approximations. The next step is to create a global overview from the national values and their uncertainties, for which additional simplifications are necessary as described above.

It is recognized that there are still some gaps and uncertainties in the inventory data that have been reported, and they include the following:

(a) Lack of data on some countries: This will result in an underestimate of total inventories — especially as there are no data from India and Pakistan, which operate nuclear power plants and are therefore expected to have some quantities of spent fuel and radioactive waste stored or disposed on their territory.
(b) Uncertainties in the translation of data from national waste classification systems to waste classification in GSG-1 [1] for aggregation purposes: This will affect the distribution of waste volumes among the various waste classes (VLLW, LLW, ILW and HLW).
(c) Differences in the way that various States report waste volumes (e.g. ‘current as stored’ volumes versus forecasted ‘as disposed’ volumes, use of actual physical volume of waste packages, versus the volume envelope it might occupy in a repository). This will affect the reported volumes of waste. On average, however, the overall effect on accuracy of the global inventories should not be significant.
(d) Different reporting dates: This will affect the accuracy of a ‘snapshot’ for a given date. However, most of the reporting dates are within a year or two of the selected reference date for this publication (31 December 2013). Given that in most cases the accumulated waste and spent fuel volumes do not grow that quickly, and the very large residual inventories in the States with large programmes, the overall effect on the accuracy of the global inventories should be insignificant.
(e) Differences in the way that certain materials, such as UMM waste, NORM and DSRSs are declared: Some States include these as special categories of waste, some include them with other categories, and some do not consider them to be radioactive waste at all. The net effect is likely to be an underestimate of the reported amounts of these materials, especially UMM waste, which is generally of high volume or mass.
(f) The inclusion of unprocessed liquid waste in the totals: In some cases, no distinction was made in country reports for unprocessed liquid waste versus solid waste. The potentially large volumes of liquid waste can distort the overall data if not accounted for separately. Therefore, liquid waste quantities are handled separately from solid waste quantities in all tables.
(g) Lack of data on conditioned DSRSs: For most countries without nuclear power, DSRSs are their major or only type of radioactive waste. However, DSRSs are comparatively insignificant in volume until they are conditioned and placed in suitable packaging for disposal.

The project supporting the development of this publication did not include a quantitative analysis of the level of uncertainty in the presented information. Lessons learned in the collection and analysis of data for this publication will be incorporated into later phases and modifications will be sought to improve accuracy and to minimize uncertainties.

6.3. CURRENT INVENTORIES OF SPENT FUEL

The spent fuel inventories provided in this publication do not distinguish between fuel considered to be a waste in the responding State and fuel that is considered to be an asset (i.e. intended to be reprocessed). The global totals include all countries where information is available. Notable exclusions are India and Pakistan. The country groupings used in the tabulation are defined in Table A–9. The data include spent fuel from nuclear power plants, demonstration and research reactors and other kinds of reactor (e.g. naval propulsion reactors and isotope production). The amount of spent fuel is presented in metric tonnes of heavy metal (t HM) and describes the mass of heavy metals (e.g. plutonium, thorium, uranium and minor actinides) contained in the spent fuel.

It should be noted that spent fuel which has been sent for reprocessing but which has not yet been reprocessed is included in the amount of spent fuel currently in storage in the country to which it has been sent. Additional data on historical amounts of spent fuel that have been reprocessed have been extracted from other sources, such as the annual reports from commercial reprocessing facilities. Spent fuel that has been reprocessed is no longer in the form of fuel, but has been separated into various types of waste and recyclable components. The unit of measure for waste from reprocessing of spent fuel is cubic metre and is included as part of the LLW, ILW and HLW, as appropriate. Fuel that has been reprocessed is not included in inventories.

6.3.1. Nuclear power plant spent fuel

Since the start of nuclear power based electricity production in 1954 to the end of 2013, a total of about 370 000 t HM of spent fuel was discharged from all nuclear power plants worldwide, excluding India and Pakistan (see Table 5, and Table A–9 for a complete breakdown of the country groupings).

TABLE 5. SPENT FUEL DISCHARGED FROM NUCLEAR POWER PLANTS (t HM), AS OF 31 DECEMBER 2013

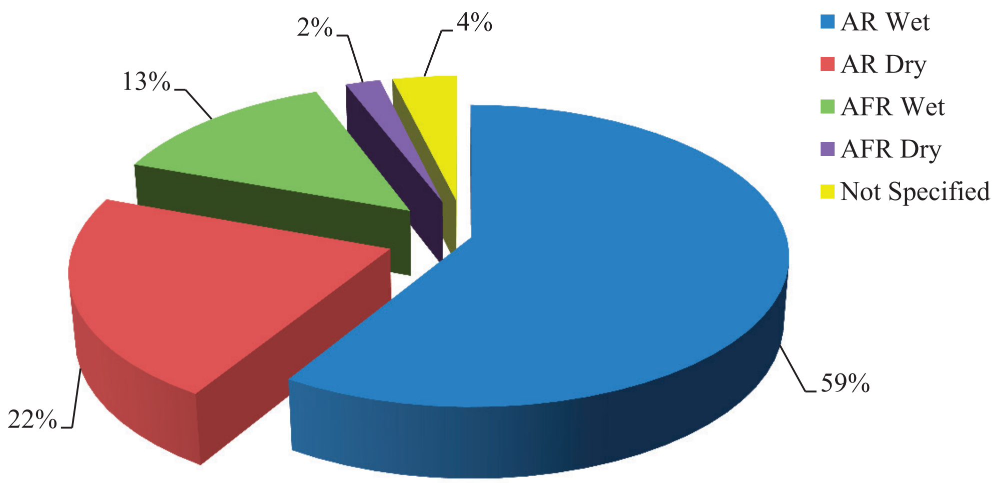
	Wet storage	Dry storage	Reprocessed	Total
Africa	850	50	n.a.[a]	900
Eastern Europe	28 600	2 700	3 200	40 000
Western Europe	37 000	4 600	108 400	154 100
Far East	32 100	5 700	8 600	46 400
North America	79 300	41 900	n.a.[a]	121 200
Latin America	3 000	2 000	n.a.[a]	5 000
Middle East and South Asia	n.a.[a]	n.a.[a]	n.a.[a]	n.a.[a]
South East Asia and Pacific	n.a.[a]	n.a.[a]	n.a.[a]	n.a.[a]
Global total	180 800	56 900	120 300	367 600
Joint Convention Contracting Parties	177 000	56 900	120 300	363 700
EU Member States[b]	43 300	6 800	107 600	162 300
OECD/NEA members	166 100	53 200	119 900	343 800

Note: Possible differences in totals are due to rounding. See Table A–9 for a complete breakdown of the country groupings. The total amounts of spent fuel in storage in Eastern Europe and Western Europe (‘Total’ column) include additional quantities (5510 t HM and 3806 t HM, respectively) for which the type of storage, wet or dry, was not specified in the relevant National Profiles. The total amounts of spent fuel in storage in Western Europe include 320 t HM currently in storage in France and the United Kingdom awaiting reprocessing and originating from outside of these respective countries.

[a] n.a.: not applicable (or none reported).

[b] Excludes Austria, Greece, Malta and the Netherlands.

About one third of all spent fuel discharged from nuclear power plants (120 000 t HM) is reprocessed. The remaining two thirds is stored pending processing or disposal. Most spent fuel is held at nuclear power plant sites in wet storage in the reactor pools. Fuel inside the reactor core is not included in the inventory, since it is not considered to be spent until it has been discharged from the core. After initial storage for cooling for at least a few years in the reactor pool, some spent fuel has been transferred to dry storage or to centralized wet storage facilities. The total amount of spent fuel in storage is about 250 000 t HM. Figure 20 shows the share of this fuel for the different types of storage. Dry storage keeps the fuel in a dry, gas cooled environment by using air or an inert gas such as nitrogen, either in a canister or vault where shielding and heat removal is provided by the canister or structure. Wet storage functions by holding the spent fuel in a water filled pool, where both cooling and shielding is provided by water.



Note: AFR — away-from-reactor; AR — at-reactor.

FIG. 20. Nuclear power plant spent fuel storage by type.

6.3.2. Spent fuel from research and other reactors

A number of States operate non-power reactors, such as research, isotope production or propulsion reactors. The spent fuel from these reactors is summarized in Table 6. It is noteworthy that these amounts are less than 1% of the amounts of spent fuel which originate from nuclear power plants. It should also be noted that the fuel quantities from non-nuclear power plant reactors are generally not publicly reported to the same level of detail as for nuclear power plants, especially when they are used primarily for military or defence purposes. However, a typical research reactor has a core capacity in the order of a few kilograms of uranium fuel, whereas a commercial nuclear power plant might have a capacity of 100 tonnes or more. Isotope production reactors may have a capacity of a few tonnes. There can also be a difference in the level or degree of enrichment of the fuel in ^{235}U. Many research reactors and isotope production reactors were originally designed to operate using high enriched uranium fuels, whereas commercial power reactors utilize low enriched uranium fuels (roughly 0.7–5%), leading to a potential difference in the amount of uranium that is discharged in the spent fuel, and also depends on the amount of ‘burnup’ of the ^{235}U.

It is evident that the majority of the spent fuel in storage from non-power nuclear reactors is in North America. This is because spent fuel from prototype power reactors is considered under the research reactor category in Canada and the United States of America. Most spent fuel from research and other reactors in many countries has been returned to suppliers for reprocessing or disposal (usually to the United States of America or the Russian Federation).

TABLE 6. SPENT FUEL STORED FROM RESEARCH AND OTHER REACTORS (t HM), AS OF 31 DECEMBER 2013

	Wet storage	Dry storage	Total
Africa	0.2	n.a.[a]	0.2
Eastern Europe	83	n.a.[a]	83
Western Europe	132	14	146
Far East	109	n.a.[a]	109
North America	37	2817	2854
Latin America	0.4	n.a.[a]	0.4
Middle East and South Asia	n.a.[a]	n.a.[a]	n.a.[a]
South East Asia and Pacific	0.3	n.a.[a]	0.3
Global total	362	2831	3193
Joint Convention Contracting Parties	150	2831	3192
EU Member States[b]	128	2	130
OECD/NEA members	360	2831	3191

Note: Possible differences in totals are due to rounding. See Table A–9 for a complete breakdown of the country groupings.

[a] n.a.: not applicable (or none reported).

[b] Excludes Austria, Greece, Malta and the Netherlands.

6.3.2.1. Long term management of spent fuels

The planned disposition of spent fuel is summarized in Fig. 21, based on the fraction of the total t HM of spent fuel that has been discharged to date. It is also possible that a State might change its plans, owing to a change in national policy; in which case, they might have a combination of reprocessing waste and spent fuel for disposal. In some States, different routes are planned for the spent fuel from different types of reactor, again resulting in a combination of reprocessing waste and spent fuel for disposal. Research reactor fuels are often returned to the country of origin; in which case, they appear in the inventory of the receiving country.

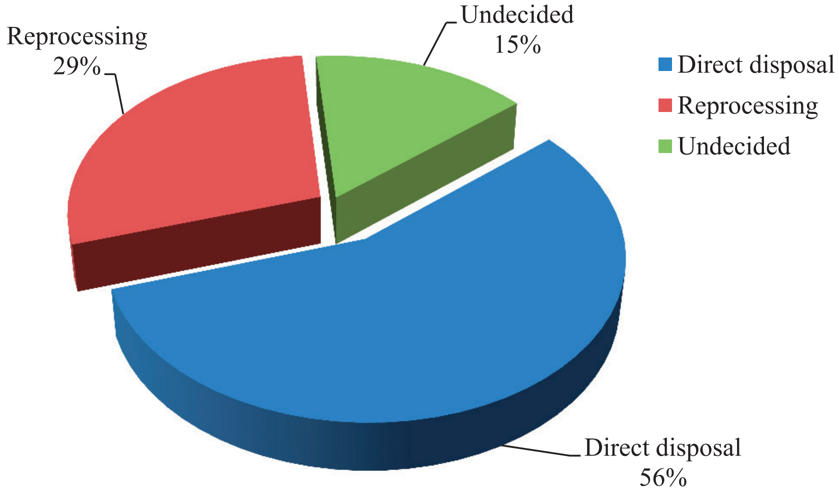


FIG. 21. Summary of existing spent fuel by planned disposition.

Waste from reprocessing is included in the inventory of radioactive waste in the country where it is currently stored. In most cases, when reprocessing takes place in a different country, the residual waste is eventually returned to the country from where the fuel originated. Several States are currently constructing or planning additional reprocessing facilities to support their expanding nuclear power programmes, including China and India (see Table 3, in Section 5.1, for the current facilities available for the reprocessing of spent fuel in France, Japan, the Russian Federation and the United Kingdom).

6.4. CURRENT INVENTORIES OF RADIOACTIVE WASTE

Most of the radioactivity present in radioactive waste (up to 95% of the total) is present in HLW (including spent fuel, when declared as waste). In terms of volume, it is the reverse, and more than 95% of the total volume of waste comprises LLW or VLLW. Accordingly, the risk presented by radioactive waste might often not be correlated with its volume. The hazard presented by any toxic agent is a complex combination of quantity, particular chemical components and their respective concentration in the waste (in this case mainly the radionuclides), physical and chemical form of the waste, and the radioactivity level. Generally, chemical and physical forms that are mobile in the environment are considered to be more hazardous on account of the ease with which disperse into the environment, increasing the likelihood of human or animal contact and exposure. Limiting mobility is an important reason for conditioning of waste prior to disposal.

Solid waste and liquid waste are described separately. This differentiation is important because of the significant volume of liquid waste and the large volume reduction achievable from processes such as evaporation, filtration, vitrification and others, depending on the chemical composition and amount of water. Typically, liquid waste is processed for solidification soon after it has been generated, rather than placing it in storage. In States which follow this approach, only a small part of the national radioactive waste inventory exists in liquid form. In some countries, a past practice was to store some waste in liquid form with the intention of processing and converting to solid form at a later stage, and as a result, the waste still exists in this form at many sites. Section 6.4.2 presents the liquid radioactive waste inventories as indicated in the National Profiles submitted.

Most radioactive waste is either in storage awaiting the development of a suitable disposal facility, is awaiting further treatment pending disposal in a licensed facility, or has already been disposed of. In general, only solid waste is placed into disposal facilities, although past practices in some countries included direct injection of liquid waste into underground formations for disposal. This strategy is still practised in the Russian Federation (see Section 6.4.2).

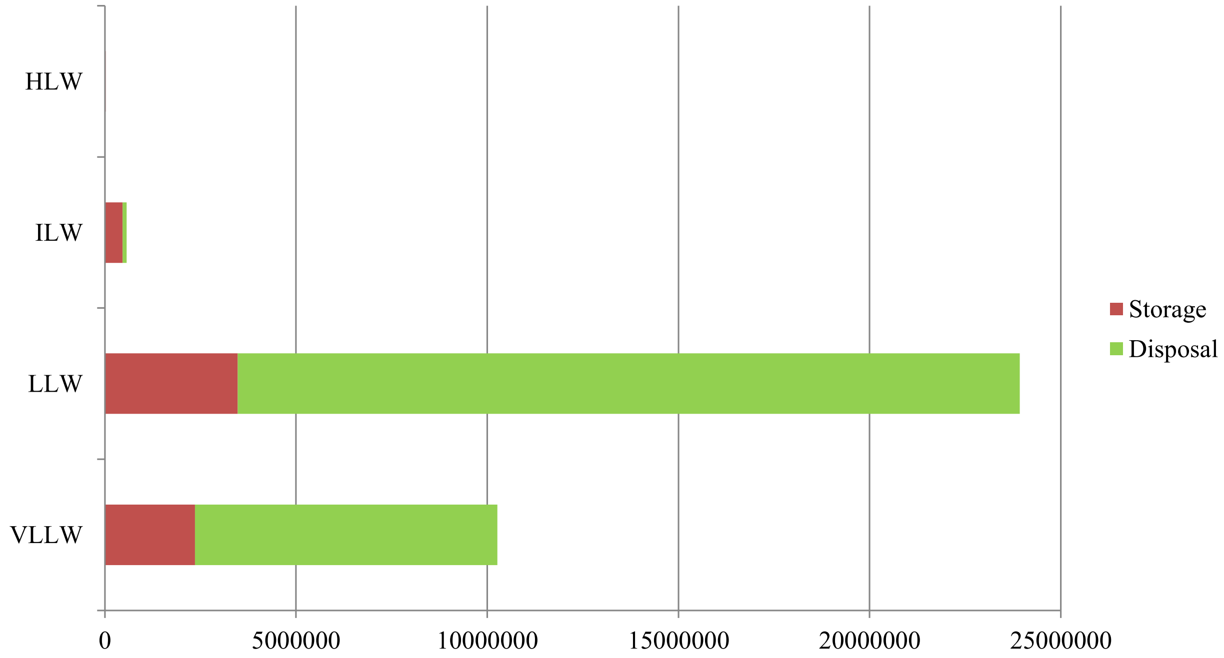
The values for storage and disposal reflect the declared status of each country. Disposal is defined as intentional emplacement in a facility without the intent to retrieve. Some States require the possibility to retrieve the disposed waste for some period of time after disposal.

6.4.1. Solid radioactive waste

Solid waste includes inherently solid materials, such as metals, plastics and other dry materials, as well as solidified liquids. In the case of unprocessed waste, and in some States, ‘solid waste’ can also include small amounts of liquids or ‘wet solids’ (such as filter cake or dewatered ion exchange resins). Figure 22, based on the National Profiles, shows the global totals of different types of solid radioactive waste in storage and disposal, as of 31 December 2013. The data shown in Fig. 22 represent ‘as disposed’ volumes, based on the conversion matrices provided by respondents (see Section 6.2.3 for a discussion of uncertainties inherent in such an approach).

It is evident that the majority of the volume of waste consists of VLLW and LLW. As noted above, most of the radioactivity is contained in the much smaller volumes of ILW and HLW. For VLLW and LLW, the majority of the waste generated has already been disposed of. For ILW and HLW, however, the majority of the waste so far generated is currently in storage awaiting the development of appropriate disposal facilities.

Table 7 summarizes the volume of solid radioactive waste in storage, and Table 8 summarizes the volume of solid radioactive waste in disposal, as of 31 December 2013. The values for the waste classes are as defined by the individual countries and the totals have been rounded to the nearest 1000 m^3. Figure 23 provides an overview of the origin of the radioactive waste in storage and disposed of in 2013, respectively.



Note: HLW storage is 22 000 m^3.

FIG. 22. Summary of global solid radioactive waste inventories (m^3).

TABLE 7. SOLID RADIOACTIVE WASTE IN STORAGE (m^3), AS OF 31 DECEMBER 2013

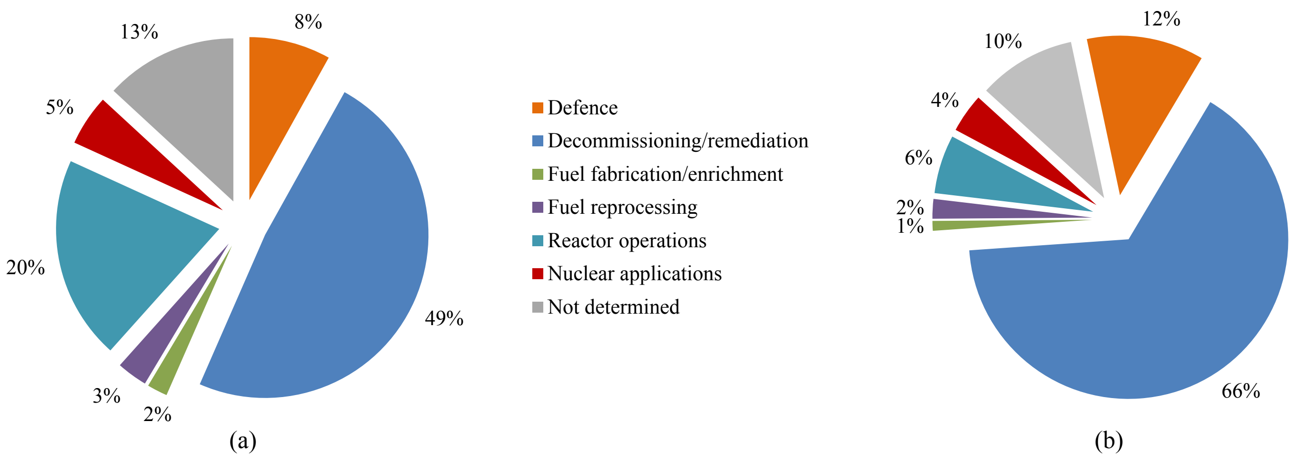
	VLLW	LLW	ILW	HLW
Africa	7 000	20 000	1 000	0
Eastern Europe	15 000	2 479 000	101 000	7 000*
Western Europe	224 000	355 000	269 000	6 000
Far East	5 000	331 000	4 000	0
North America	2 105 000	248 000	84 000	8 000
Latin America	0	37 000	0	0
Middle East and South Asia	0	3 000	0	0
South East Asia and Pacific	0	5 000	1 000	0
Global total	2 356 000	3 479 000	460 000	22 000
Joint Convention Contracting Parties	2 355 000	3 404 000	459 000	22 000
EU Member States	237 000	426 000	276 000	6 000
OECD/NEA members	2 340 000	2 191 000	441 000	17 000

Source: National Profiles and NEWMDB.
Note: Possible differences in totals are due to rounding.
* This figure includes approximately 4000 m^3 of unconditioned HLW in Ukraine, which resulted from the Chernobyl accident. Following the accident, this material was emplaced in engineered surface trenches. It will need to recovered and emplaced in a deep geological repository, when this becomes available in the future.

TABLE 8. SOLID RADIOACTIVE WASTE IN DISPOSAL (m^3), AS OF 31 DECEMBER 2013

	VLLW	LLW	ILW	HLW
Africa	0	14 000	0	0
Eastern Europe	1 000	911 000	7 000	0
Western Europe	277 000	1 990 000	8 000	0
Far East	800	63 900	0	0
North America	7 174 000	17 464 000	91 000	0
Latin America	1 500	4 500	0	0
Middle East and South Asia	0	0	0	0
South East Asia and Pacific	452 000	4 000	0	0
Global total	7 906 000	20 451 000	107 000	0
Joint Convention Contracting Parties	7 906 000	20 421 000	107 000	0
EU Member States	278 000	2 022 000	9 000	0
OECD/NEA members	7 905 000	19 540 000	100 000	0

Source: National Profiles and NEWMDB.
Note: Possible differences in totals are due to rounding.



Source: National Profiles and NEWMDB.

FIG. 23. Radioactive waste inventory by origin in 2013, (a) stored and (b) disposed.

6.4.2. Liquid radioactive waste

While most States process liquid radioactive waste into solid form within a short time of it being generated, a few — notably, the United States of America and the Russian Federation — have large volumes of liquid waste in long term storage. Much of this waste results from defence activities and is only now being dealt with through the design, construction and licensing of liquid waste treatment facilities [27, 28].

Table A–10 summarizes the quantities of liquid radioactive waste declared by various countries. Note that these are the current ‘as stored’ volumes. It generally does not include liquids held in short term storage awaiting processing. It is difficult to estimate the final ‘as disposed’ volumes, since this will largely depend on the eventually selected processing and conditioning methods. In most cases, this will result in a very large reduction in the final volume for disposal assuming that evaporative or filtering type processes will be used to separate or concentrate the radioactive elements from the bulk liquid. In other cases, the liquid waste might be conditioned in situ (e.g. by cementation), which can result in a volume increase. In addition, the classification of the final waste form (VLLW, LLW, ILW or HLW) will also depend on the length of time the waste has been in storage (i.e. radioactive decay time), the efficiency of the treatment process and the degree of volume reduction achieved.

Table A–11 summarizes the liquid waste which has been disposed of by injection into deep wells, based on data provided in the Joint Convention national reports provided by the Russian Federation and the United States of America [27, 28] and on analysis performed by the IAEA, using source data from publicly available literature on the Russian Federation [29, 30].

6.4.3. Uranium mining and milling waste

Amounts of residual material from UMM are very large compared to the standard waste classes. UMM waste is also not uniformly considered as waste by all States: some consider UMM waste as a special byproduct or as material containing NORM. This is in line with the approach laid out in the Joint Convention [5], which does not apply to waste that contains only NORM and that does not originate from the nuclear fuel cycle, unless it is declared as radioactive waste. UMM waste, rounded to the nearest one million tonnes, is shown in Table A–12. The values for storage and disposal of UMM waste are based on how each State declares its inventory.

6.4.4. Disused sealed radioactive sources

DSRSs are usually recorded by number of pieces, rather than by volume, because the relative volume of a source is very small (<10 cm^3). There are different options used for the management of DSRSs: some States do not include these in their radioactive waste inventories, while others do. These are presented separately where possible; however, where DSRSs are defined as radioactive waste and reported as part of the standard waste classes, these are reflected in the relevant national inventory within the standard waste classes.

The DSRSs can include a wide range of radioisotopes, from relatively innocuous short lived sources to high energy sources designed for gamma irradiation and sterilization of materials. Some States provide a breakdown of the sources, while others do not publicly report them. For many non-nuclear power countries, the DSRSs represent their entire radioactive waste inventory.

6.5. NUMBER OF RADIOACTIVE WASTE DISPOSAL FACILITIES

There are several facilities in operation or under construction around the world for managing various categories of waste. All States with nuclear power programmes have access to waste processing and storage facilities for all of their waste. However, not all States have access to disposal facilities for all waste types (see Table A–13 for a summary of the status of disposal facilities).

In November 2015, the Government of Finland granted a licence for the construction of a repository for spent fuel (deep geological repository). A number of other States have an active siting process for such a facility, and a few have selected a site and are currently in the licensing process. Note that ‘Construction’ in Table A–13 means that a facility is either in construction or under licensing, ‘Closed’ in Table A–13 means that a facility is either closed or under institutional control. Note that a facility will dispose a range of wastes according to its design and operating licence. In Table A–13, the facilities have been divided into two groups: near surface disposal (NSD) and geological disposal (GD). It should be noted that GD includes both intermediate depth and deep geological repositories, as confinement is not solely a function of depth but also host rock and hydrogeology, among other factors. Table A–13 is based both on the National Profiles on the CD-ROM accompanying this publication and information published in NEWMDB. The capacities are listed where this information was available.

Some States used to dispose of LLW (and some ILW) by dumping at sea, and the first reported sea disposal operation of radioactive waste took place in 1946. This practice was discontinued in 1993 by international agreement (see Ref. [12]). By then, 14 States had used more than 80 sites to dispose of approximately 8.5×10^4 TBq of radioactive waste (see Refs [31, 32] for global inventories of radioactive waste disposed of at sea).

7. FUTURE FORECASTS

In order to plan adequately for the long term management of radioactive waste, it is necessary to forecast the waste quantities expected in the future. This is often not an easy task, especially for States with numerous and diverse activities that result in the creation of radioactive waste and with many different organizations involved in producing and managing it. For many States, radioactive waste generation is closely related to electricity production from nuclear power plants and thus future forecasts are closely related to the predictions of the future use of nuclear power. These predictions can be made quite accurately in the short term, a few tens of years, but have substantial uncertainties when it comes to predictions over longer time spans. Correspondingly, the radioactive waste predictions have similar uncertainties.

States significantly involved in the initial development of nuclear power, whether for defence or civilian purposes, may also need to deal with significant quantities of waste associated with the decommissioning and remediation of facilities and sites that are no longer in use or will be in the future. In many cases, including China, France, the Russian Federation, the United Kingdom and the United States of America, these amounts of waste will likely be significantly greater in volume (although not in radioactivity) than existing waste from nuclear power generation.

It is nevertheless important to make predictions of future waste arisings and to update them at regular intervals as the environment and boundary conditions change for nuclear power production and other uses of radioactive material. This is important for the planning of facilities needed for storage, treatment and disposal and for establishing adequate funding for future waste management. It should also be recognized that precise numbers are not required to establish a reasonable basis for predicting future needs, as long as the inherent uncertainty in the quantity of future waste arisings is acknowledged. In due course, more precise data on waste volumes and radioactivity levels will be needed at the time of licensing of such facilities.

Defining the planning assumptions is thus often a difficult task. A major aspect to consider is the timeframe for the forecast: the longer the forecast, the less accurate it will be. The amounts and composition of waste from different practices will vary according to:

— How facilities operate;
— Industrial and technical processes that generate the waste;
— Policy and regulations governing the industry, technology and waste management;
— The economics of different areas of the waste management cycle and waste management philosophies.

In developing forecasts of future waste quantities, the following considerations need to be addressed:

(a) Planning scenarios for future generation of electricity from nuclear energy (e.g. high, low and best estimates, and constraints);
(b) Future operating strategies for the facility, such as the merits of waste minimization versus cost minimization;
(c) Timing of activities that impact on waste arisings, such as short term versus delayed strategy for remediation actions and solutions;
(d) Practical tools for creating forecasts (e.g. historical data, data from similar countries and facilities, and engineering estimates);
(e) Modelling and process mapping (e.g. understanding the route through different waste management systems and the impacts of this on forecasts);

(f) Accuracy requirements (e.g. significance of impact on the waste owner or WMO if estimates are significantly too high or low).

In general, a 'bottom up' forecasting approach provides the greatest accuracy and facilitates the highest degree of flexibility. Using this approach, individual waste streams or categories are estimated at a facility level, and then aggregated with other waste streams to produce an overall estimate. Initial estimates for planning purposes can also be derived by extrapolating past history, taking into account the number of facilities operated and their lifetimes; this latter approach is often simpler and more pragmatic. Estimates of future waste arisings should include all activities and life cycle phases of a facility that result in the production of radioactive waste, such as operation, maintenance, refurbishment and decommissioning.

Compared to LLW and ILW, spent fuel arisings are somewhat easier to forecast. The amount of spent fuel produced is usually proportional to the amount of energy extracted from it. With knowledge of the number and type of reactors and their historic fuel burnup levels, a reasonable forecast can be made of future spent fuel arisings for the remaining lifetime of a reactor. In some countries, the forecasting of waste volumes has been performed over many years and is regularly published. Other States have only recently begun to undertake rigorous forecasting activities and thus no detailed reporting has occurred. Consequently, not all States have reported forecasts in the National Profiles. It should be noted that the Joint Convention [5] does not require the reporting of forecasts, only values of presently stored and disposed waste. However the Euratom Waste Directive [6] requires forecasts of future generation of radioactive waste be reported.

Table A–14 provides a summary of current and future amounts of spent fuel in storage and disposed of by 13 States, as provided in the National Profiles. Future updates of this publication will build on these initial estimates to provide a more comprehensive picture. Table A–15 provides forecasts for spent fuel and for different classes of radioactive waste (converted from national classification schemes to GSG-1 [1], where necessary), together with summary information on the main assumptions used for the predictions.

8. TRENDS AND CHALLENGES

This is the first Status and Trends publication of the series, so trends cannot be presented based on a previous version. During the preparation of this publication, however, certain challenges and general trends were identified, both of which can be tracked for the future. Trends and challenges were also discussed during the Fifth Review Meeting of the Contracting Parties to the Joint Convention [7], in May 2015, the meetings of Radioactive Waste Technical Committee (WATEC) of the IAEA in April 2014, July 2015 and April 2016, and the IAEA sponsored International Conference on Advancing the Global Implementation of Decommissioning and Environmental Remediation Programmes in May 2016. The following trends and challenges presented here are based on this.

8.1. GENERAL TRENDS AND CHALLENGES

There has been progress in most countries in the formulation of national policies, strategies and programmes for the management of spent fuel and radioactive waste which are based on international recommendations. Particularly in Europe, the requirements of the Euratom Waste Directive [6] harmonizes the approaches and reporting in EU Member States.

Public acceptance of spent fuel and radioactive waste management remains a challenge in most countries. This is especially true for disposal facilities, and a lack of acceptance has had a negative impact on the progress of programmes. Efforts have been increased to enhance openness, transparency and public involvement. In the cases where progress is reported, local acceptance has been successfully achieved. There has been notable progress in Finland, where a licence to construct a deep geological repository for spent fuel was granted in 2015; as well as in France and Sweden, which have both selected sites for their deep repositories and are progressing with the licensing steps.

Funding for waste management and decommissioning activities still remains a challenge in a number of countries. Good systems have been created for spent fuel and radioactive waste from current nuclear power production through contributions to dedicated waste management and decommissioning funds, but funding for decommissioning of old reactors and for remediation and management of legacy sites and waste remains a challenge, especially when the original owner or operator no longer exists. In these cases, funding often becomes the responsibility of the State and must compete with other funding priorities.

To avoid repeating the creation of unfunded legacy sites in the future, States planning to embark on nuclear power or constructing new reactors are increasingly considering future requirements for the management of spent fuel and radioactive waste as well as eventual decommissioning as a precondition to licensing the new reactors. They are strengthening policies, strategic planning and financing systems to ensure that future waste management and decommissioning needs can be adequately met. Where such policies and systems do not exist, they are being developed.

Peer reviews have been an important, yet generally voluntary, aspect of planning, implementing and assessing radioactive waste, spent fuel and decommissioning programmes around the world for many decades. They continue to be used to develop and improve national programmes and are now a required element in many countries under various legal instruments, such as the Euratom Waste Directive [6].

8.2. MANAGEMENT AND DISPOSAL OF SPENT FUEL AND HIGH LEVEL WASTE

8.2.1. From nuclear power plants

In some countries, clear decisions on the policy to reprocess or directly to dispose of the spent fuel have been made. However, the issue remains open in many countries, and storage will continue until a decision is made and the selected approach is implemented. Although the rate at which spent fuel is being reprocessed is more or less constant, the trend since 2007 has been that fewer States send their spent fuel for reprocessing and that the amount of spent fuel in long term storage is increasing. Many States face delays in their programmes for HLW and spent fuel disposal for a variety of technical and sociopolitical reasons. This has resulted in the need for more and longer storage of spent fuel and HLW until disposal facilities are available.

The length of the storage period could be many decades. The challenge is thus to ensure the long term safety and integrity of the storage facilities and the fuel for many decades to come. The challenge goes beyond the storage facility: the spent fuel will have to be transported, encapsulated and then possibly transported once again to the final disposal (if the encapsulation facility is not co-located with the disposal facility). The greatest challenge is handling spent fuel after a long period of interim storage. As the requirements for storage capacity increase, new storage is being built outside of the reactor buildings. Most of these are facilities for dry storage, but some pool facilities are also being built.

8.2.2. From research reactors and other special reactors

The amount of fuel from research reactors and other special reactors is normally much less than the fuel from nuclear power reactors. The specific challenges of this fuel are mainly the higher enrichment and different composition compared with fuel from nuclear power reactors. Although research reactors are often built in countries with a nuclear power programme, research reactors also exist in countries with a small nuclear infrastructure. In these countries, the research reactor fuel might be the most important waste management issue.

At present, most research reactor fuel is returned to the country of origin of the fuel, mainly the Russian Federation and the United States of America, and thus it does not require disposal in the country where it has been used. Some States have decided to reprocess research reactor fuel. Others, however, have to consider disposal of this fuel nationally, which can be challenging.

8.2.3. Spent fuel and high level waste disposal

In Finland, France and Sweden, good progress is being made in the development of disposal facilities for spent fuel and HLW, with licence applications filed or under preparation for specific sites — the granting of a construction licence in Finland in 2015 is a milestone of global importance. Globally, programmes are often subject to unanticipated delays and, in some cases, the process of site selection has been completely restarted based on revised approaches to combining technical and volunteer based approaches. Such delays have increased the time schedules for disposal projects in most countries, encompassing a variety of reasons, including the duration of siting activities, time needed for adequate public engagement, technical and regulatory aspects. For the latter, the lack of experience of licensing such facilities is a challenge. In addition, once a site has been chosen and accepted by the public, maintaining public acceptance over the duration of the project will also be a challenge, since it will extend many decades to perhaps a century or more in some cases.

The primary consequence of the delays in implementing disposal is that more of the spent fuel and HLW is stored for longer periods and new storage facilities have to be built. The longer storage, however, also has a beneficial aspect, as it reduces the radioactivity and subsequently the heat load that will be emplaced in the disposal facility. Most designs for spent fuel and HLW disposal are strongly influenced by the heat load of the waste and a reduction in heat load makes the disposal facility more compact and, in some respects, easier to design.

8.3. MANAGEMENT AND DISPOSAL OF INTERMEDIATE LEVEL WASTE

Paragraph 2.2 of GSG-1 [1] defines ILW as “Waste that, because of its content, particularly of long lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal.” This waste mainly comes from reprocessing of spent fuel, discarded reactor core components, defence activities, dismantling of nuclear reactors (including after an accident), and cleanup of highly contaminated sites.

Many industrial scale methods exist for safe processing, packaging and storage of ILW. Only one disposal facility for ILW currently exists. Two more are under licensing or construction, and a licence application will soon be filed for a fourth facility (these all are for combined ILW and LLW disposal). It should be noted that there are existing facilities which can be designed for ‘ILW’ as designated in a national classification system, but these are typically considered to be LLW facilities under the waste classification in GSG-1 [1].

Normally the volumes of ILW are small compared to LLW and VLLW, typically less than 5% of the total. However, special challenges are connected to some categories with relatively larger volumes (e.g. graphite from gas cooled reactors and radium bearing waste from earlier radium production). Although the radioactivity levels in some of the waste can be relatively low, it is composed mainly of long lived radionuclides, such as ^{14}C and ^{226}Ra (and decay products) and is therefore managed as ILW.

8.4. MANAGEMENT AND DISPOSAL OF LOW AND VERY LOW LEVEL WASTE

Paragraph 2.2 of GSG-1 [1] defines LLW as waste that “requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities”, and VLLW as waste 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”. LLW and VLLW comprise the vast majority of the volume of radioactive waste, with more than 95% of the global inventory. However, it generally contains less than 5% of the total radioactivity.

Numerous industrial scale methods exist for the safe processing, packaging and storage of the LLW and VLLW. In many countries, disposal facilities have been in operation for many years. Some States do not distinguish between LLW and VLLW, so they dispose of them in the same facility; others have separate facilities for the two types. Lately, the interest in separate VLLW disposal facilities has increased and the classification systems in some countries have been changed to include VLLW as well. This is generally done for optimization purposes, since a facility specifically built for VLLW can be simpler and therefore less costly than a facility for LLW. Larger volumes of VLLW are expected in the future as a result of decommissioning and dismantling programmes.

Most disposal facilities for LLW are surface or near surface facilities (including relatively shallow depth, underground caverns). In several countries, however (e.g. Germany and Switzerland), the choice has been made for disposal of this waste in deeper rock caverns. Several new disposal facilities are under licensing, construction and start of operation, and many more are in the planning or siting stages. Disposal of VLLW and LLW in countries with small quantities of waste remains a challenge owing to the relatively high initial fixed cost to site, design, licence and construct a repository.

8.5. DECOMMISSIONING, DISMANTLING AND MANAGEMENT OF WASTE

More than half of the operating reactors currently in the world are older than 30 years [33]. Therefore, the decommissioning of nuclear facilities is gaining importance as an increasing number of reactors and related facilities are being permanently shut down, or will be in the near future. An increase in decommissioning activities results in greater challenges for planning, dismantling, funding and, in particular, waste disposal. In some cases, a lack of disposal sites blocks or delays the start of dismantling. Preparedness to accommodate large quantities of waste for disposal over a fairly short period of time will be important — in particular in States that foresee an accelerated decommissioning programme for nuclear power plants. In addition, much of the waste produced as a result of dismantling a nuclear facility is different than normal operational waste, with a higher proportion of metals (e.g. equipment) and building rubble. Waste minimization efforts through effective application of sorting, decontamination, recycling and reuse will become a very important part of a decommissioning waste management strategy to minimize the burden on disposal facilities. Availability of skilled resources is also being cited as a challenge. Along with the ageing reactors, the experienced personnel are also ageing, and often their accumulated knowledge is crucial to safe dismantling of a facility.

Decommissioning and dismantling of reactors damaged in an accident represents a particular challenge. The International Research Institute for Nuclear Decommissioning (IRID) was established in Japan in 2013 to coordinate and fund relevant R&D activities, primarily for the decommissioning of the damaged Fukushima reactors. In 2014, the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF) was given the remit by the Japanese authorities to oversee the development of a strategic plan for decommissioning and the planning of research and development activities.

8.6. MANAGEMENT OF WASTE FROM NUCLEAR ACCIDENTS

The volumes of waste that arise owing to a nuclear accident are much larger than those typically resulting from nuclear power plant operation and dismantling. Their physical and chemical form is also different. The accidents at the Chernobyl and Fukushima Daiichi nuclear power plants highlight the need for appropriate contingency planning: although each accident is different, basic contingency planning can be done at a national level to determine responsibilities and general strategies in the unlikely event of such an occurrence. Decisions made in the early stages of the accident, for example while attempts are still being made to control or mitigate any consequences, can have significant implications on the later waste management and restoration steps (e.g. recovery of hastily dealt with materials for final conditioning and disposal).

Accidents requiring radiological cleanup are not limited to reactor accidents. There have been numerous instances where DSRSs, some with very high radioactivity contents, have been inadvertently opened and the contents dispersed by unsuspecting individuals. These are different to deal with than reactor accidents, since they are usually not reported until sometime afterwards (e.g. when a member of the public is treated for acute radiation sickness), and the patterns of contamination dispersion are more random and unpredictable.

8.7. MANAGEMENT OF DISUSED SEALED SOURCES

Sealed sources are used in practically every country for various industrial and medical practices. For many countries, these are the only radioactive material to be handled, and they require storage and eventually disposal. Most high activity sealed sources are returned to the country where they were manufactured and will thus be included in the waste management system of that country. However, orphan sources and sources of lower activity remain a challenge for some States. The disposal of DSRSs is still a challenge in most countries, and new concepts are currently being tested (e.g. borehole disposal for DSRSs) where this is an issue.

8.8. MANAGEMENT OF URANIUM MINING AND MILLING WASTE AND NATURALLY OCCURRING RADIOACTIVE MATERIAL WASTE

Practices governing the management of UMM waste and NORM vary widely by State: some consider these to be included in their VLLW, LLW or ILW inventories; some have a separate class of waste for one or both of them, and others do not consider them to be radioactive waste at all.

UMM waste is normally stored or disposed of at or near the mines or the uranium extraction facilities, normally in near surface facilities. Disposal in the original underground uranium mine workings is also practised. In modern mines, this is carefully controlled, implemented and regulated. However, challenges exist with UMM waste from earlier activities in several countries, not least concerning the responsibilities and the funding. Most mines have an operational life of 10–20 years at most, after which the mining companies might cease to exist. If funds for waste management have not been set aside during the operation of the mine, responsibility generally reverts back to the State. In countries with a long history of uranium extraction, this financial burden can be significant.

NORM waste is produced by a number of extractive industries, such as oil and gas, hard rock mining, phosphate mining, as a byproduct of the mining or extractive process due to the naturally occurring uranium and its decay products in the rocks. Management and disposal of NORM and radium bearing waste continues to be a challenge in several countries. However, there are also several specially built disposal sites for NORM waste (e.g. Gulen repository, Norway, and Banjaran Kledang repository, Malaysia).

8.9. MANAGEMENT OF LEGACY SITES AND WASTE

In many countries, there is legacy waste from earlier nuclear activities and from contaminated sites. Much of this waste is poorly characterized (e.g. radioactivity content and chemical composition) and can exist in substantial quantities (e.g. contaminated soils and liquid waste in tanks). Many of these sites date back to the very early years of nuclear research and original records of waste and how it was managed might have been lost (e.g. hand written records that have been discarded or damaged by fire, flood and pest infestation). The management and disposal of this waste are challenging, both technically and financially. A variety of techniques, ranging from complete recovery and remediation to in situ disposal have been implemented. Each case is unique and requires a thorough understanding and evaluation of the consequences of the various options (e.g. removal versus leaving it in place).

9. CONCLUSIONS

This publication provides an overview of the status of radioactive waste management globally and presents global estimates of the amounts of residual radioactive material accumulated by nuclear activities. Significant progress has been achieved, particularly during the last 10–20 years, in the treatment, conditioning and storage of spent fuel and radioactive waste and in developing national inventories. There has also been progress in emplacing certain radioactive waste, except HLW and spent fuel, in final disposal facilities. In the case of HLW and spent fuel, research undertaken over several decades has progressed to the point that a number of geological disposal facilities are expected to be licensed for operation over the next ten years.

The data presented in Section 6 provide a comprehensive overview and a best available estimate of the amounts of spent fuel and radioactive waste that currently exist in the world. The main source of information used for inventories and forecasts is the National Profiles on the CD-ROM accompanying this publication. Information about inventories in States which did not submit a report is taken from the reports to the Joint Convention, NEWMDB and other publicly available sources.

Worldwide, there is an estimated 250 000 t HM of spent fuel in storage and 120 000 t HM of reprocessed spent fuel, and volumes of radioactive waste, both in storage and in final disposal, are summarized in Tables 9 and 10.

TABLE 9. RADIOACTIVE WASTE IN STORAGE (m^3)*

	Solid	Liquid	Total
VLLW	2 356 000	None reported	2 356 000
LLW	3 479 000	53 332 000	56 811 000
ILW	460 000	6 253 000	6 713 000
HLW	22 000	2 786 000	2 808 000

* Given as disposed or disposable volumes (i.e. including the volume of packaging for disposal).

TABLE 10. RADIOACTIVE WASTE IN DISPOSAL (m^3)*

	Solid	Liquid	Total
VLLW	7 906 000	None reported	7 906 000
LLW	20 451 000	39 584 000	60 035 000
ILW	107 000	8 628 000	8 735 000
HLW	0	68 000	68 000

* Given as disposed or disposable volumes (i.e. including the volume of packaging for disposal).

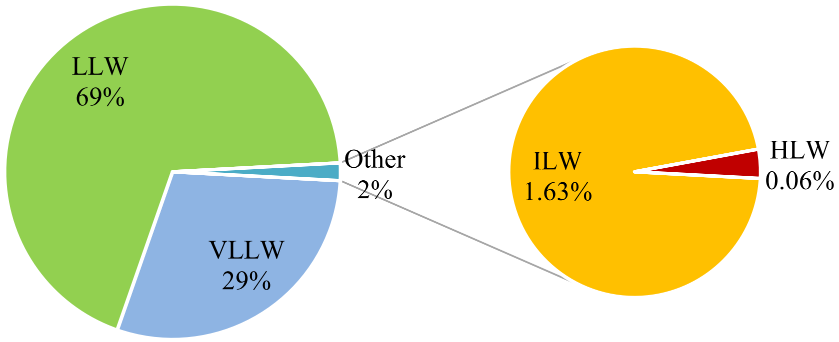
9.1. SPENT FUEL

By the end of 2013, it is estimated that approximately 370 000 t HM of spent fuel was discharged from the world's nuclear reactors. More than 98% of this is from nuclear power plants, with the remainder coming from research, isotope production and naval propulsion reactors. Of the 370 000 t HM, approximately one third (120 000 t HM) has been reprocessed, resulting in the separation of fissile materials and residual waste, which is included in the reported radioactive waste inventories. The remaining two thirds is currently being stored, awaiting either future direct disposal or reprocessing — this total does not include all discharges of spent fuel from military production reactors, as such data are generally not reported publicly. However, the waste generated from the reprocessing of military spent fuel is often included in the reported national inventories.

9.2. RADIOACTIVE WASTE

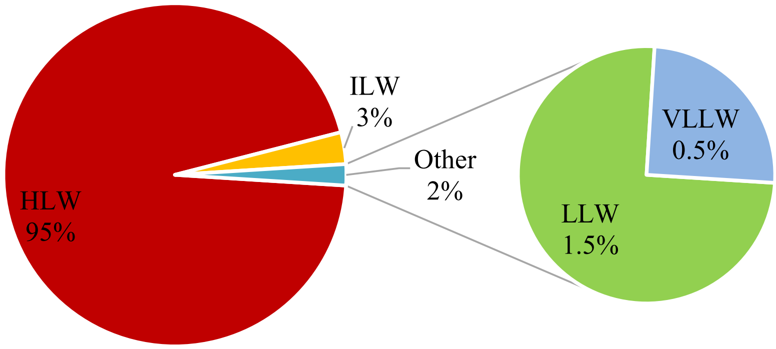
The estimated global inventories of solid radioactive waste are summarized in Tables 9 and 10. The conversion of the national radioactive waste management classification schemes into the radioactive waste classifications provided is based on the translation matrices provided by each respective State. Estimates were made for States that did not provide a conversion matrix from data taken from the publicly available national reports under the Joint Convention [5].

It is evident that most current VLLW and LLW have already been disposed, while most current ILW and HLW are in storage awaiting the development of suitable disposal facilities in the coming decades (see Fig. 24). Most of the radioactivity associated with radioactive waste is ILW and HLW: while VLLW and LLW comprise more than 95% of the total volume of waste, ILW and HLW typically comprise more than 95% of the total radioactivity (see Fig. 25).



Source: National Profiles and NEWMDB.

FIG. 24. Share of total waste volumes in storage and disposal.



Source: National Profiles and NEWMDB.

FIG. 25. Distribution of waste radioactivity based on the waste classes.

The global inventory of UMM waste reported in the National Profiles as radioactive waste is approximately 1.2 billion tonnes, with 75% reported as being in storage and 25% reported as being in final disposal. However, not all States classify UMM waste as radioactive waste and thus do not include this in their waste inventories.

With respect to the future forecasts presented in Section 8 and Table A–15, too few States have provided data to draw any specific conclusions about forecasts of future inventories. However, some general conclusions can be drawn. Most of the world's current nuclear fleet will reach end of life within the coming decades. This will result in a large increase in the rate of arising of radioactive waste originating from decommissioning projects, notably VLLW and LLW from dismantling of nuclear structures. This trend is an inevitable consequence of the first generation of nuclear power plants reaching the end of their design lives, and will be reinforced by the change of nuclear policy in some countries which requires early shut down of reactors. In addition, many States are now making concerted efforts to clean up past nuclear legacy sites. This will also result in an increase in future volumes of radioactive waste. Future spent fuel and nuclear power plant operational waste arisings will depend on the plans to build new nuclear power plants.

It is anticipated that subsequent versions of this publication will present a fuller picture of future global inventories because new legal instruments, such as the Euratom Waste Directive [6], now require that future forecasts of waste and spent fuel arisings be reported.

There remain uncertainties about total global amounts of radioactive waste because not all States have provided national waste inventories. Additional uncertainty results from the need to convert data presented according to national classification systems into a common system based on the waste classification scheme of GSG-1 [1]. Finally, uncertainty also arises from the need to present waste quantities according to the anticipated 'as disposed' volumes. Despite these uncertainties, available data are sufficient to provide a clear representation of the global situation in terms of the overall challenge represented by the radioactive waste that currently exists and to provide an indication of challenges that will arise in the future as facilities still in operation, or planned, come to an end of their useful lives.

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Annex

CONTENTS OF CD-ROM

The Status and Trends project was launched by the IAEA in collaboration with the European Commission and the OECD Nuclear Energy Agency in June 2014 with the aim of providing an overview of the current global status and trends in spent fuel and radioactive waste management, and includes information on current inventories, expected future waste arisings and strategies for the long term management of these materials.

The results of the project, provided in this publication, are based primarily on National Profiles submitted by each of the 47 Member States which participated in the project. The National Profiles, provided on the CD-ROM accompanying the publication, generally present data using a common reference date, December 2013, this being the reference date for data presented in reports to the Fifth Review Meeting of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management which took place in Vienna in May 2015.

The information in Tables A–1 to A–15 is based on the National Profiles and reports to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.

The National Profiles reflect information and data as provided by each participating Member State. The views expressed do not necessarily reflect those of the IAEA. The use of particular designations of countries or territories does not imply any judgement by the IAEA as to the legal status of such countries or territories, of their authorities and institutions or of the delimitation of their boundaries.

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ABBREVIATIONS

DSRS	disused sealed radioactive source
Euratom	European Atomic Energy Community
EW	exempt waste
HLW	high level waste
ILW	intermediate level waste
LLW	low level waste
MOX	mixed oxide
NEWMDB	Net Enabled Waste Management Database
NORM	naturally occurring radioactive material
OECD	Organisation for Economic Co-operation and Development
OECD/NEA	OECD Nuclear Energy Agency
t HM	tonnes of heavy metal
UMM	uranium mining and milling
VLLW	very low level waste
VSLW	very short lived waste
WMO	waste management organization

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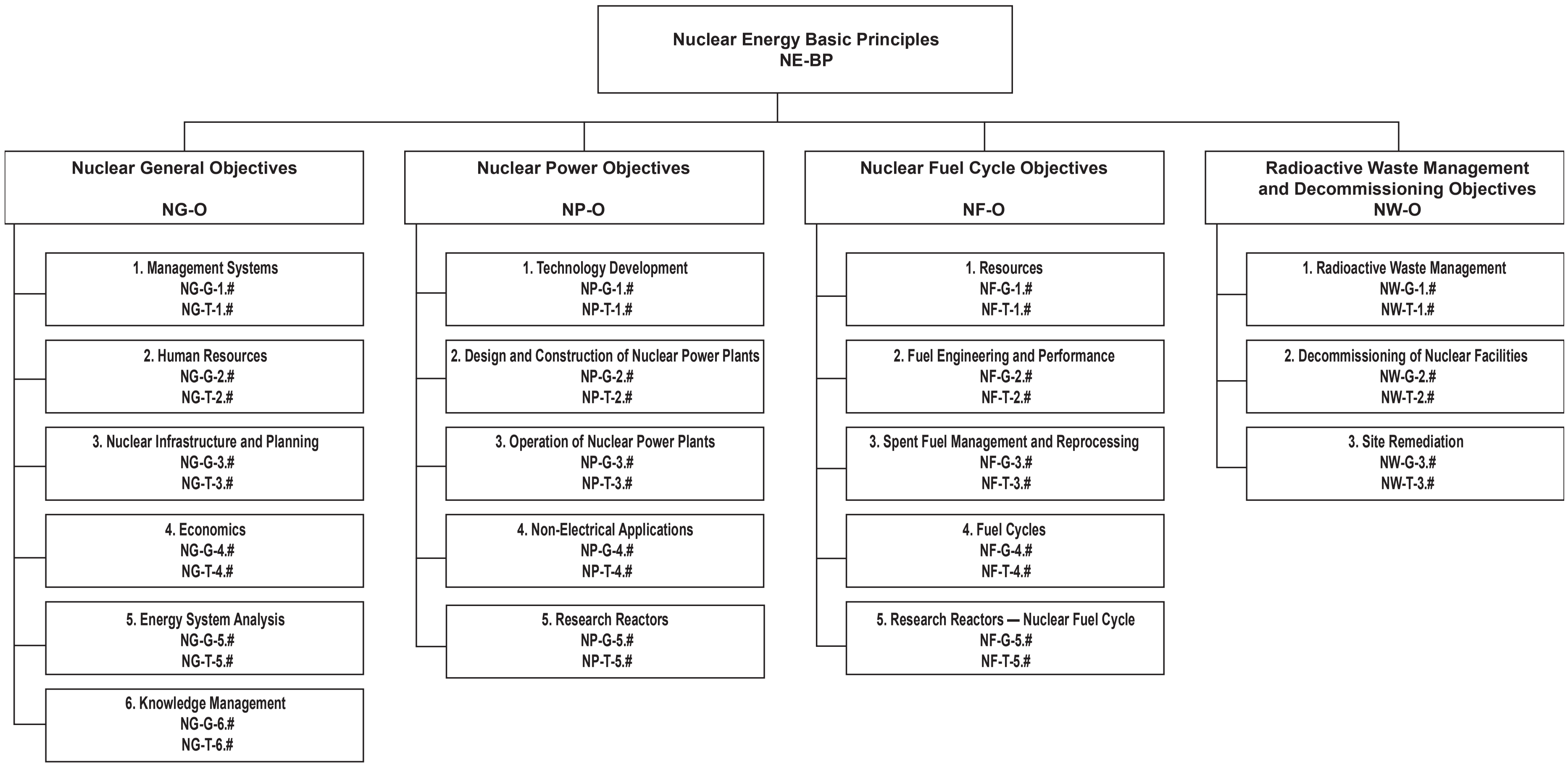

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