TECHNICAL REPORTS SERIES NO. 240

Guidebook on Spent Fuel Storage Options and Systems

3rd Edition

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GUIDEBOOK ON SPENT FUEL STORAGE OPTIONS AND SYSTEMS

Third Edition

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FOREWORD

Nuclear power can help to address the twin challenges of ensuring reliable energy supplies and curbing greenhouse emissions. The nuclear power reactors in operation today supply more than 10% of the world's total electricity and a third of all low carbon power. Nuclear power will continue to play a key role in the world's low carbon energy mix for decades to come. Since the inception of nuclear power, spent fuel has been generated and spent fuel storage has been a necessary step in all spent fuel management strategies. Since the 1950s, spent fuel has been stored safely and securely in a variety of wet and dry storage systems, with around 70% of the global inventory currently in storage pending decisions or implementation of decisions on its management and disposition.

In recent decades, the operating environment of nuclear power plants has continued to move toward increasing fuel cycle efficiencies through generally higher fuel burnup, which puts greater demand on the adopted spent fuel management strategy and on spent fuel storage systems. In addition, the duration of spent fuel storage is not currently defined in some instances, partly due to the long lead time to develop a deep geological repository, which subsequently impacts the handling and transportation of spent fuel in the long term.

This Technical Report is the third edition of the Guidebook on Spent Fuel Storage; earlier editions were published in 1984 and 1991. It aims at providing guidance to Member States on spent fuel storage options, describing the history and observed trends of spent fuel storage technologies, gathering operational experiences and lessons learned, observing the evolving aspects related to higher burnup and mixed oxide spent fuel and the extension of the storage time frames. It also includes information on the distribution of the current global inventory of spent fuel by storage systems and a description and terminology of available spent fuel storage technologies and different storage facility locations.

This information will enable Member States to prepare for and manage spent fuel storage issues and challenges, especially those countries embarking on nuclear power, to make the best sustainable decisions in managing their spent fuel.

The IAEA wishes to express its appreciation to everyone who took part in the preparation and review of this publication. The IAEA officer responsible for this publication was A. González-Espartero of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

1.1. BACKGROUND

Spent nuclear fuel (SNF) storage is a necessary step in any spent fuel management strategy. Around 70% of the spent fuel generated by nuclear power plants (NPPs) worldwide is accumulating in storage, pending decisions or implementation of decisions on spent fuel for recycling[1] or disposal. Although in recent years there has been a slight decrease in the amount of SNF being generated due to a combination of the more efficient use of nuclear fuel in the reactors and a number of NPPs shutting down, spent fuel generation still far exceeds existing and near future reprocessing and disposal capacities. Due to the demand for clean energy and the positive ratio of the number of new connections and reactors under construction[2] to those permanently shut down, the trend of spent fuel accumulating in storage is set to continue. The resulting uncertainties relative to the duration of the storage period and the amount of spent fuel in storage for the next decades create new considerations to be taken into account during the design and operation of spent fuel storage facilities.

During the first two decades of the 2000s, the NPP operating environment continued to move in the direction of ever increasing fuel cycle efficiencies, in particular through higher fuel burnups and other approaches to increase fuel efficiency which generally require increased fuel enrichment. Such developments reduce the amount of spent fuel relative to the energy being produced but put greater demands on the adopted spent fuel management strategy and on spent fuel storage systems. As higher burnup fuel produces greater decay heat, recent loss of cooling assessments in some countries have led to a drive to reduce stocks of spent fuel held in at-reactor (AR) storage facilities in order to increase safety margins. This, coupled with a saturation of AR storage capacities (as a result of NPP life extensions, delays to the implementation of back end steps or delays in achieving approval for higher density storage) has led to increasing need for additional storage capacity through away from reactor (AFR) storage facilities. At the same time, many of the first storage facilities in operation are reaching the end of their initial licence period and are undergoing a process of renewal, with some renewals already completed.

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[1] In the scope of this publication, no distinctions are made between reprocessing and recycling; any mention of reprocessing infers the subsequent recycling steps.

[2] In 2020 there were five new connections to the grid, three NPPs started construction and six NPPs were permanently shut down (Source: https://pris.iaea.org/).

Over the 2020s, the nuclear power community looks to welcome a number of new reactors built in embarking countries.[3] The sharing of operating experience, lessons learned and advice is essential for these countries to make the best sustainable decisions in managing their spent fuel.

The responsibility for establishing and implementing the overall strategy for the management of radioactive waste from NPPs is allocated to the operator [1]. The IAEA's Specific Safety Guide SSG-15, Storage of Spent Nuclear Fuel [2], describes these responsibilities in relation to spent fuel, including determining the overall strategy for its management. Development of this strategy needs to take into account the national radioactive waste management policy, interdependences among all steps in waste management and the available options [1]. To discharge this responsibility, it is important to have the latest information on the options available for managing spent fuel. The present publication provides an updated overview and technical information on spent fuel storage options.

1.2. OBJECTIVE

The overall objective of this publication is to provide guidance to Member States on SNF storage options. This is approached by providing an update to the Guidebook on Spent Fuel Storage (IAEA-TRS-240) published in 1991 [3], describing the history and observed trends of spent fuel storage options and gathering operational experiences and lessons learned. The evolving aspects related to higher burnup and mixed oxide (MOX) spent fuel and the extension of the storage time frames are also covered.

This enables Member States to better prepare for and manage spent fuel storage issues and challenges.

Guidance and recommendations provided here in relation to identified good practices represent expert opinion but are not made on the basis of a consensus of all Member States.

1.3. SCOPE

This guide is limited to storage of SNF from commercial power reactors. Storage of SNF from research and prototype reactors is not specifically covered here, although the storage technologies described may also be applicable for these spent fuels.

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[3] In 2020, the embarking countries United Arab Emirates (19 August 2020) and Belarus (3 November 2020) connected their first units to the grid (Source: https://pris.iaea.org/).

Inventory data within this publication has been taken from the country reports provided for the Seventh Review Meeting of the Contracting Parties to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (Joint Convention) with a reporting date of 31 December 2019, unless other data was publicly available. Values used in the figures have been rounded, as those are intended to illustrate trends rather than displaying exact inventories.

The inventory data presented have been split into the following regions:

- Africa: South Africa;
- Asia and the Pacific: China, Japan, Republic of Korea;
- Eastern Europe and Central Asia: Armenia, Bulgaria, Czech Republic, Hungary, Kazakhstan, Lithuania, Romania, Russian Federation, Slovakia, Slovenia, Ukraine;
- North America: Canada, United States of America (USA);
- Latin America: Argentina, Brazil, Mexico;
- Western Europe: Belgium, Finland, France, Germany, Italy, Netherlands, Spain, Sweden, Switzerland, United Kingdom of Great Britain and Northern Ireland (UK).

1.4. STRUCTURE

Section 2 of this publication provides a general overview of spent fuel storage, including an introduction to terminology, and an overview of spent fuel arisings and trends. Section 3 describes the different storage technologies. Section 4 presents safety considerations related to spent fuel storage. Section 5 describes ageing related impacts for both fuel and storage systems as well as introducing surveillance, maintenance and repair, and data preservation. Section 6 highlights considerations relating to transport of spent fuel after storage. Section 7 presents aspects associated with security and safeguards. Section 8 outlines economic considerations for spent fuel storage. Section 9 concludes with future developments in spent fuel storage.

The appendices contain more detailed information and examples of different storage systems (both conceptual and operational) for different fuel types (Appendix I), regulations and guidance for spent fuel storage and transport (Appendix II), examples of design basis accidents (DBAs) involving spent fuel handling (Appendix III), reported materials performance data (Appendix IV) and IAEA publications relating to spent fuel storage (Appendix V).

2. SPENT FUEL STORAGE

Nuclear fuel that can no longer efficiently sustain nuclear fission and cannot be used as fuel in its present form is termed 'spent fuel' [4]. The decay of radioisotopes that are present results in high radioactivity and heat, therefore spent fuel requires a minimum storage period prior to the implementation of a disposition path (recycling or disposal). Storage of spent fuel is defined in the IAEA Safety Glossary as "the holding of… spent fuel in a facility that provides for its containment, with the intention of retrieval" [4]; spent fuel storage is by definition an interim step. However, the term 'interim storage' is widely used to refer to an intermediate storage step before spent fuel disposition is implemented.

Once spent fuel is removed from the reactor, a period of time is required for the initial decay of radioisotopes to enable it to be loaded into a cask for transport, either to further storage, a reprocessing facility for subsequent recycling, or to a conditioning facility for disposal. This initial decay of radioisotopes is predominately undertaken underwater in spent fuel pools located next to the reactor vessel. Spent fuel storage pools have the capability to manage high heat loads and provide flexibility for future handling. The exceptions are gas cooled reactors [5], in which the initial decay of radioisotopes in fuel stringers is undertaken in carbon dioxide cooled decay tubes before the stringer is broken down and transferred to the reactor pool for further decay.

A range of terms are used to describe the options available for locating spent fuel storage facilities. These are described below and depicted in Fig. 1 [6, 7]:

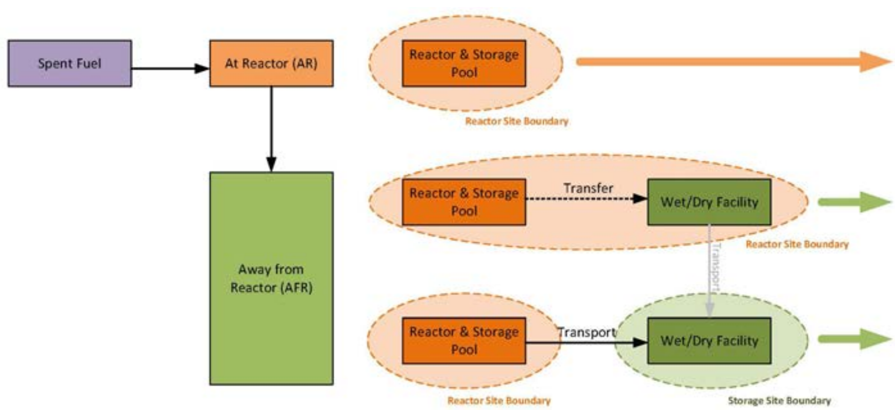

FIG. 1. Options for spent fuel pathways, all leading to future disposition.

— AR storage: a pool co-located with the reactor, inside the containment building.
— AFR storage: a wet or dry storage facility that is not co-located with the reactor.[4] The fuel has to be transferred or transported[5] to the storage facility. There are two classifications of AFR storage facilities: reactor site (RS) and off site (OS):
- AFR-RS storage occurs in a facility located within the reactor site boundary. Spent fuel is transferred from one facility to the other. A further distinction can be made for an AFR-RS in terms of those that stand alone and can still support operations if the reactor is decommissioned, and those which are reliant on reactor services.
- AFR-OS storage involves a facility located outside the reactor site boundary. In this case, spent fuel is transported on public roads.

2.1. SPENT FUEL ARISINGS

By December 2019, over 400 000 tHM of spent fuel had been discharged globally from nuclear power reactors. About two thirds of this amount remains in

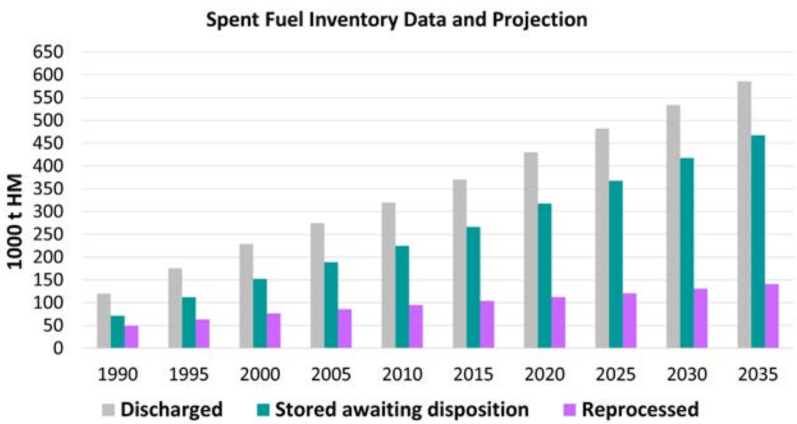

FIG. 2. Spent fuel arisings inventory data and projections.

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[4] In the USA, this is often referred to as an 'independent spent fuel storage installation' (ISFSI).

[5] In the scope of this publication, the term 'transfer' refers to on-site relocation (i.e. within the boundaries of the NPP site) and the term 'transport' refers to an off-site relocation (i.e. over public roads).

storage, while about one third has been reprocessed [8]. Projections of spent fuel discharge, reprocessing and storage are reflected in Fig. 2.

2.2. ALTERNATIVES FOR SPENT FUEL STORAGE

Storage of spent fuel for periods of 50 to 100 years is technically possible and supported by research findings and operational experience [9]. However, storage capabilities do not justify indefinite deferral of spent fuel management policy decisions or their implementation [10].

A variety of spent fuel storage facilities have been designed and built in Member States with nuclear power programmes.

Wet storage is by far the most common form of storage, with all power reactors having a spent fuel pool associated with reactor operations. This is not surprising, as most large commercial plants have light (or heavy) water reactors in which the fuel is designed to dwell in water for long periods without deterioration. Water is an effective shielding and coolant material, is readily available and is easily cooled and purified. The water also provides a transparent medium to facilitate fuel handling and visual observation.

AR storage capacity is required for any spent fuel management strategy (recycling or disposal), as the amount of heat and radiation generated by the spent fuel needs to decay to levels that would permit the transition of spent fuel to the next step of the fuel cycle.

The capacity of AR storage pools varies among countries and reactor types. They can range from a modest storage capacity to provide short term buffer storage before transport to a disposition facility or an AFR storage facility to a capacity sufficient to store a significant proportion of the reactor's lifetime arisings. The initial capacity is generally related to the fuel cycle policy that was in place when the NPP was designed. In addition to the determined storage capacity, there will be a requirement to reserve space for unloading the full core inventory.[6] New fuel or partly used fuel can be temporarily stored in the pool as part of plant operating inventory, reducing the net capacity available for AR spent fuel storage. In recent years, AR storage has been used to full capacity in some cases, threatening the continued operation of the power plants. If AR capacity is insufficient for lifetime spent fuel arisings or the subsequent disposition facility is unavailable, and if options for increasing pool capacity have been exhausted, AFR storage will be necessary.

Two approaches have been developed for AFR storage facilities, using either wet or dry systems, as seen in Fig. 1. In the first approach, additional

[6] This requirement applies to water cooled reactors.

storage capacity is constructed at the RS, separated from and largely or entirely independent of the reactor building. Examples of AFR-RS facilities are the shared pool at the Tihange multireactor site (Belgium) and the dry storage facilities at Darlington NPP (Canada) and Trillo NPP (Spain). After completion of reactor operations, AFR-RS storage facilities can continue to store spent fuel safely until the fuel can be removed from the site (e.g. storage at Trojan NPP (USA)).

The second category of AFR storage is a storage facility constructed at a location outside of the reactor site boundary (OS). In this case, spent fuel may have to be transported on public roads. A significant proportion of wet AFR-OS capacity is in the form of pools at reprocessing plants, for example in France, the Russian Federation and the UK,[7] which can receive fuel from both domestic and foreign utilities.

Alternatively, an AFR-OS installation can be a centralized facility to receive fuel from the NPPs operating across a country, such as Clab (Sweden). AFR-OS storage facilities based on dry storage technologies are also in operation, for example at Zwilag (Switzerland), Ahaus (Germany) and Mining Chemical Complex (Russian Federation).

AFR spent fuel storage can fulfil a variety of purposes, depending upon the particular set of needs or situation. AFR storage primarily acts as a buffer between AR storage and the next step in the fuel cycle: reprocessing or disposal. The location of the AFR facility (either RS or OS) depends upon many factors, which are discussed in more detail in Section 2.4.

As of December 2019,[8] about[9]half of the global spent fuel inventory remains in AR pools, while the other half is stored at AFR storage facilities. About 33% of spent fuel stored at AFR storage facilities is stored wet, while the other 67% is in dry conditions (Fig. 3). While initial AFR storage facilities were based on wet technology, dry storage technologies of varying types have been developed since the mid-1980s and are now widely deployed. The need to

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[7] The AFR storage pool is still in operation following closure of the reprocessing facilities.

[8] Spent fuel inventory data in this publication corresponds to December 2019 (Reports for the Joint Convention’s 7th Review Meeting).

[9] List of countries in each region reporting to the Joint Convention 2019:

Africa: South Africa;

Asia and the Pacific: China, Japan, Republic of Korea;

Eastern Europe and Central Asia: Armenia, Bulgaria, Czech Republic, Hungary, Kazakhstan, Lithuania, Romania, Russian Federation, Slovakia, Slovenia, Ukraine;

Latin America and the Caribbean: Argentina, Brazil, Mexico;

North America: Canada, USA;

Western Europe: Belgium, Finland, France, Germany, Italy, Netherlands, Spain, Sweden, Switzerland, UK.

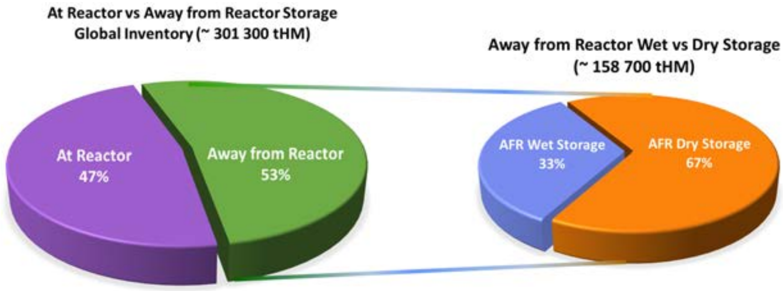


FIG. 3. Distribution of the global SNF inventory between AR and AFR storage facilities (wet and dry), 2019.

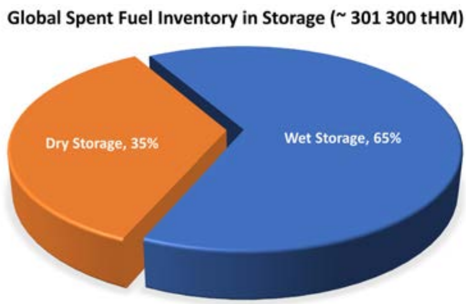


FIG. 4. Distribution of the global SNF inventory between wet and dry storage, 2019.

provide safe and effective spent fuel storage is just as important now as it was decades ago, however the situation of the nuclear power industry has evolved with the availability of new technologies to respond to these challenges.

Distribution of the global spent fuel inventory in both AR and AFR between wet and dry storage is shown in Fig. 4.

There are countries, such as the USA and Canada, where the preferred technology for AFR storage is dry. Although not necessarily apparent from Fig. 5, this has also been the trend since about 2000 for small and medium nuclear programmes as well as embarking countries.

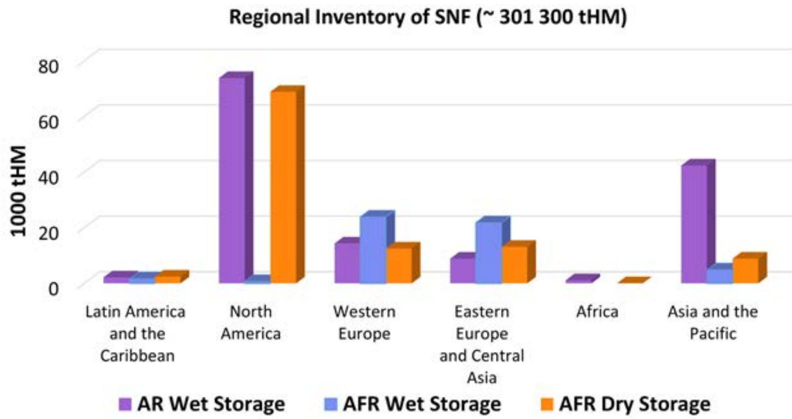


FIG. 5. Inventory of spent fuel stored in wet and dry conditions by region, 2019[9]*.*

2.3. SELECTION CRITERIA FOR AWAY FROM REACTOR STORAGE

This section provides guidance on the criteria to be considered in developing a list of spent fuel storage options and downselecting to a preferred option.

The task of identifying storage requirements, including safety and technical requirements, would be the foremost challenge to any licensee looking to implement AFR storage, irrespective of whether they intend to self-manage such projects or outsource them to the storage service provider sector. Selection of the spent fuel storage option(s) is a critical step in the back end of the fuel cycle and is a decision that needs to be made in cognisance of the subsequent steps of the spent fuel management strategy. It depends on a number of technical and non-technical factors.

The basic non-technical factors that define the spent fuel storage scenario are the following:

— National spent fuel management policy and strategy;
— Stakeholder involvement;
— Early regulatory engagement;
— Early engagement with safeguards;
— International obligations and regional cooperation;
— Economic considerations;
— Time available until the facility has to operate (otherwise known as the need by or required by date);
— Availability of a design licensed for a particular fuel;
— Licensability;

- Inventory of fuel to be stored;
- Uncertainty of future requirements.

The following technical factors have to be addressed:

- The type and characteristics of the fuel to be stored:
  - Physical features such as fuel type, cladding type, fuel geometry, post-irradiation form, compositions and mass;
  - Initial enrichment of the fuel and the discharge burnup (composition, materials, isotopes, etc.);
  - Irradiation history of the fuel, such as residence time in the core, the linear power rating and use of reshuffling schemes;
  - Residual heat;
  - Information regarding any defective or leaking fuel, with the potential for waterlogging (which is an important consideration for long term safety requirements);
  - Any unusual features of particular fuel assemblies, such as experimental design assemblies, boosters, manufacturing issues and enhanced susceptibility to corrosion.
- Site selection:
  - Site infrastructure and constraints;
  - Susceptibility to natural hazards (e.g. earthquakes, tornadoes, tsunami);
  - Transportation considerations (access and egress).
- Long term considerations:
  - Maintainability;
  - Ageing management programme (AMP);
  - Intermodal transfers (e.g. storage/transportation interfaces);
  - Decommissioning.
- Required throughput rate;
- Security considerations.

Learning from experience has shown that consideration needs to be given to selecting an AFR facility with the capability to both increase its capacity and extend its operating lifetime.

Further guidance is provided in IAEA Nuclear Energy Series NF-T-3.3 Storing Spent Fuel Until Transport to Reprocessing or Disposal [10] and IAEA-TECDOC-1558 Selection of Away-from-Reactor Facilities for Spent Fuel Storage [11]. Some general advice is provided in the IAEA Technical Reports Series No. 378 Options, Experience and Trends in Spent Fuel Management [6].

3. SPENT FUEL STORAGE TECHNOLOGIES

When spent fuel is initially discharged from the reactor, it is transferred to the AR pool. After a period of cooling, spent fuel can then be moved to dry storage or to another wet storage facility, if required. There are different dry storage designs that have been developed and are deployed around the world; the main types are described in Section 3.2. A primary differentiator between dry storage systems is those that are transportable once loaded with spent fuel and those that are not.

3.1. WET STORAGE

Wet storage is implemented in both AR and AFR storage facilities. The period of time that spent fuel resides in a pool varies between pool types and designs and the individual country's spent fuel management strategy. In general, storage pools have a reinforced concrete structure and can be modular, composed either of one large pool or several pools interconnected by transfer channels. The characteristics of a typical pool are shown in Fig. 6 and examples are shown in Fig. 7.

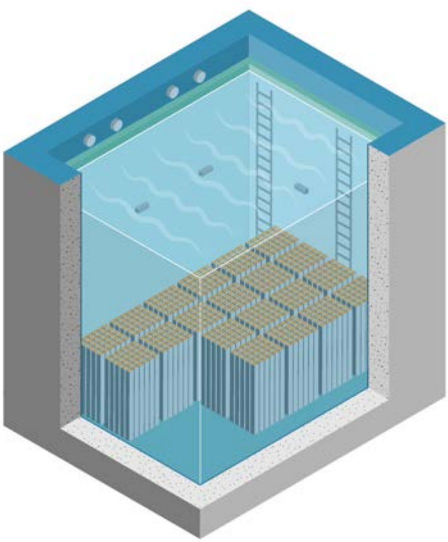
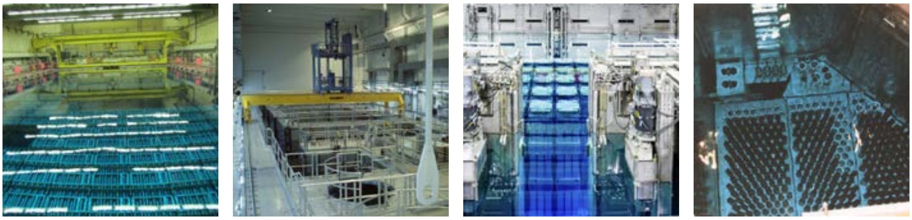


FIG. 6. Internal structure of a wet storage pool.



(a) (b) (c) (d)

FIG. 7. Examples of the spent fuel storage pools: (a) CANDU spent fuel pool Darlington Nuclear Generating Station (courtesy of OPG); (b) TVO's KP1 (photo courtesy of TVO); (c) Pool gate at Orano La Hague Reprocessing Facility (courtesy of Eric Larrayadieu); (d) water-water energetic reactors (WWER spent fuel pool at PAKS).

Most AR storage pools were constructed at the same time as the reactor and are designed to be fully integrated with reactor operations and so are built at a height that allows for easy connection with the reactor vessel. At many reactors, their initial AR storage pool capacity has been increased through means such as re-racking into a higher density array, inserting neutron absorbing materials or applying analytical means (e.g. burnup credit). AR wet storage experience now exceeds 60 years, and useful information can be found in Refs [7, 12].

A variety of AFR wet storage facilities are in use, which provide extended operational capacity to reactors once their AR pool is full, act as a centralized facility or serve as a storage buffer at a reprocessing facility. Distribution of spent fuel inventory in AFR pools by regions is shown in Fig. 8. AFR spent fuel storage pools can be located above ground, semiburied or underground; the Clab centralized facility in Sweden is located wholly underground. While some early

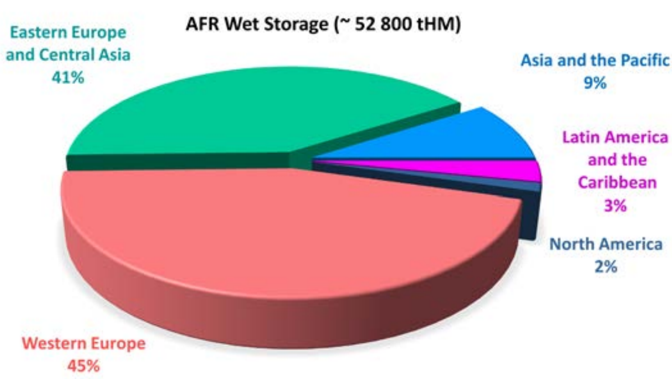


FIG. 8. Regional distribution of AFR inventory in wet storage, 2019.

FIG. 9. Pressurized water reactor (PWR) storage rack. Courtesy ANAV (Asociación Nuclear Ascó – Vandellós II).

AFR pools were open to the atmosphere, operational experience and the need to control pool water purity resulted in all new pools having a covering building. Both the pool's reinforced concrete structure and the covering building require seismic qualification as per the requirements of the national regulator. Depending upon national safety requirements, additional requirements on withstanding the impact of a design basis aircraft may apply.

Most fuel storage pool designs are similar: rectangular in horizontal cross-section and 10 m to 13 m deep. As spent fuel contains fissile isotopes, the overall storage array in both AR and AFR pools is determined by criticality considerations and takes into account the use of neutron absorbing materials, fuel spacing and (in some cases) burnup credit. To maintain the prescribed fuel spacing, fuel assemblies are placed in storage racks or baskets placed at the bottom of the pool (Fig. 9). These can generally be described as:

- — Racks: a fixed array of storage cells in the base of the pool.
- — Baskets: a movable feature holding a number of spent fuel assemblies.
- — Trays (Canada Deuterium Uranium (CANDU)): storage structures that can hold 24 fuel bundles in two rows of 12 each.

Mechanical handling systems are used to insert or remove the assemblies from the racks or baskets vertically. CANDU fuels are stored horizontally in trays, which can be stacked one on top of the other.

The following features can be found in a typical wet AFR storage facility:

- Cask reception, decontamination, loading and unloading, maintenance and dispatch;
- Underwater spent fuel storage (pool);
- Auxiliary services, such as radiation monitoring, water cooling and purification, radioactive waste handling, and ventilation, power supply.

The spent fuel can be transported to the AFR facility using a transport cask, and this may be undertaken with the fuel wet or dry. The fuel can be removed from the transport cask as either individual assemblies or within a multielement canister. Two types of cask unloading methods are in operation: wet and dry.

Most pools are lined with stainless steel, however, some pools are coated with either epoxy or alkyd resin based paint systems [12]. The lining or coating is functional: it prevents the leaching of chemicals from the structural reinforced concrete walls into the pool water (which can affect fuel integrity), it minimizes or prevents activity ingress into the pool structure and it minimizes water seepage from the pool. Stainless steel linings are preferable due to their better shock resistance and increased support to the overall structural integrity. They have proven to be the most effective to facilitate decontamination and prevent pool structure corrosion at the so-called wind/waterline — the interface between the pool water and the air above the pool [13]. In instances where the main pool is resin coated, a stainless steel liner is used at operating areas where there is greater potential for contamination or mechanical damage, for example cask and fuel handling areas.

AFR pools are filled with deionized water, with the use of additives being dependent on the type of fuel to be stored and the method of water treatment adopted. The water chemistry may require the maintenance of specific parameters, such as pH, and periodic measurement of others, such as conductivity, chloride concentration, dissolved iron and oil products. Fuel degradation can be minimized by maintaining acceptably low levels of aggressive anions such as chloride and sulphate. Water chemistry maintenance also ensures water clarity and discourages the occurrence of microbiological organisms; chemical dosing can be used to treat microbiological growth if it occurs.[10]

Water activity levels are maintained as low as reasonably achievable (ALARA) by either in-pool or external ion exchange systems and by limiting activity release to the bulk pool water.

[10] There needs to be careful consideration of the dosing chemicals used to control biological growth and the potential impact on the stored fuel, as some chemicals contain high levels of chloride.

An integrated leakage collection system may be used to monitor seepage from the pool; any pool water that is recovered may be returned to the pool after treatment.

Damaged or failed fuel, as defined in IAEA Nuclear Series NF-T-3.6 [14], may be isolated from the bulk pool water. The most common technique is to 'can' the fuel assembly or rods. Newer applications include extracting the damaged or failed rods from the assembly and incorporating them into a 'quiver', which has similar dimensions and features to a fuel assembly. Both techniques provide either a physical or gas seal between the spent fuel and the bulk pool water.

The initial storage rack or baskets in many light water reactor (LWR) spent fuel pools were designed on the basis of fresh fuel characteristics as a passive subcriticality design measure, leading to low storage densities. With the need to store greater quantities of fuel, subcriticality has been assured for higher storage densities by using neutron absorbing materials in storage racks and baskets, and by using burnup credit assumptions.

For zirconium and stainless steel clad LWR spent fuels, performance in wet storage remains excellent with no generic failure mechanism identified or experienced. In the case of stainless steel clad advanced gas cooled reactor (AGR) spent fuel, there is more than 30 years of wet storage experience. Storage performance is good, provided the fuel is stored in the presence of a corrosion inhibitor [15].

3.2. DRY STORAGE

Development work and progress on a variety of dry storage technologies has been intensive in recent decades. For practical and economic reasons, various dry spent fuel storage technologies have been developed to meet the specific requirements of different reactor fuels such as maximum allowable cladding temperature and the cover gas environment (air, CO_2 or helium).

Initially, dry storage systems were designed to have a single purpose — to provide AFR storage. As an alternative to single purpose (storage only) systems, dual purpose cask (DPC) designs followed (e.g. DSC in Canada, TN-24 in France, CASTOR in Germany and NAC-STC in the USA), which allowed for storage and transport in the same cask without the need to rehandle the fuel assemblies. Dry storage systems designed to meet disposal requirements, in addition to storage and transportation, are referred to as multipurpose casks; these systems are conceptual at present, as the disposal stage has yet to be implemented.

The loading of fuel and drying is undertaken in the spent fuel pool (depending on the type of system, further steps may be required once removed from the pool). With respect to the subsequent handling of the fuel, two major types of dry storage system can be distinguished:

— Bare fuel systems: The fuel is stored within a single unit (e.g. a DPC) that provides all safety functions such as containment and shielding and is closed using a bolted lid. The entire system can be stored and transported as a single package.
— Canisterized systems: The fuel is stored within a thin-walled canister that is welded closed post-drying. The canister provides a containment function, but shielding is provided by either a storage or transport overpack (e.g. cask or storage module). The canister has to be moved between the storage shielding structure and the transportation overpack for subsequent transport. Where canisters are used in storage systems for CANDU fuels, these are often referred to as 'baskets'.

In both types of systems, internal baskets can be used to maintain the fuel in a subcritical array and may contain neutron absorbing materials. It is very important to eliminate water and humidity when moving spent fuel to a dry storage system so as to minimize any degradation effects on the spent fuel and system components [16].

The sequence of typical canister loading is shown in Fig. 10.

Classification of currently available dry storage technologies are shown in Fig. 11 along with examples of different commercial designs.

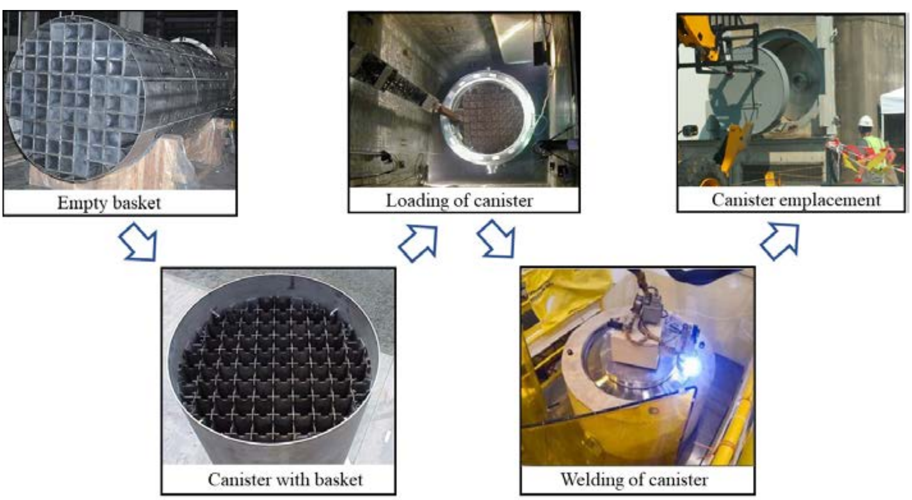


FIG. 10. Example of major steps of loading spent fuel into a canister based system (courtesy of Orano Federal Services).

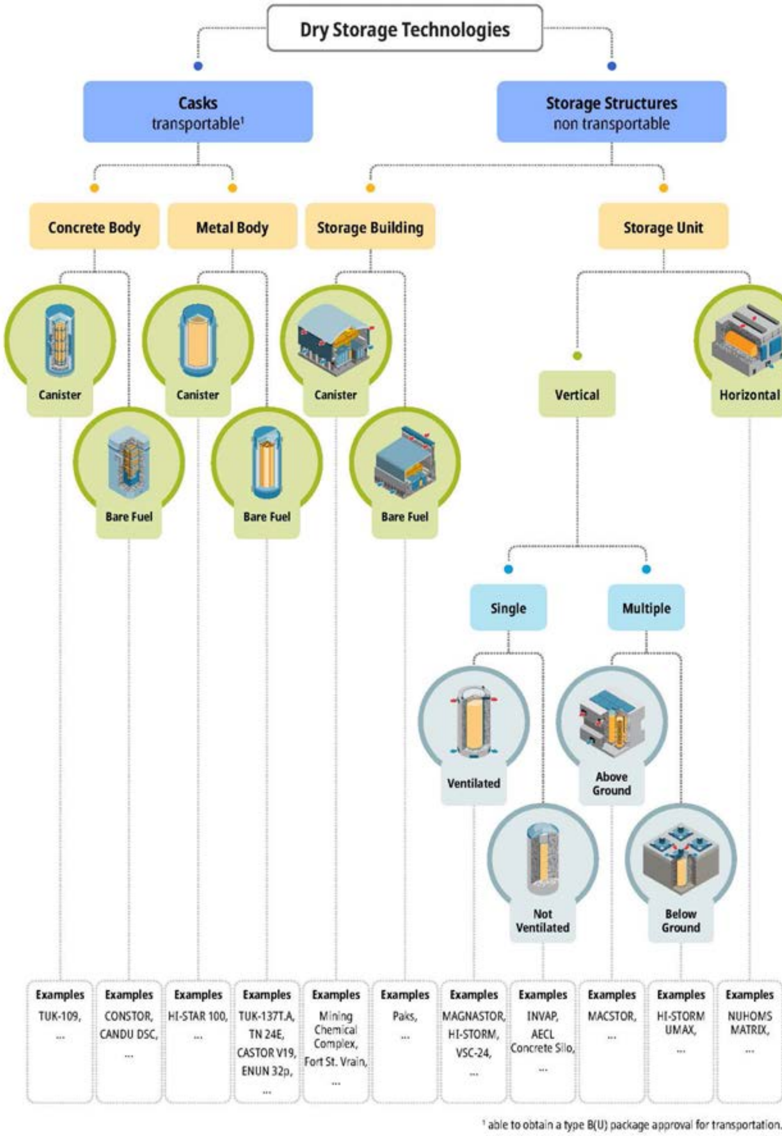


FIG. 11. Dry storage technologies available in 2023.

The timeline of dry storage system evolution is illustrated in Fig. 12. The first dry storage facilities implemented were dedicated storage buildings (vaults) around 1970 (Wylfa Magnox NPP, UK) followed by the use of vertical storage units (silos) for storage of CANDU fuel in 1977. Horizontal storage units and

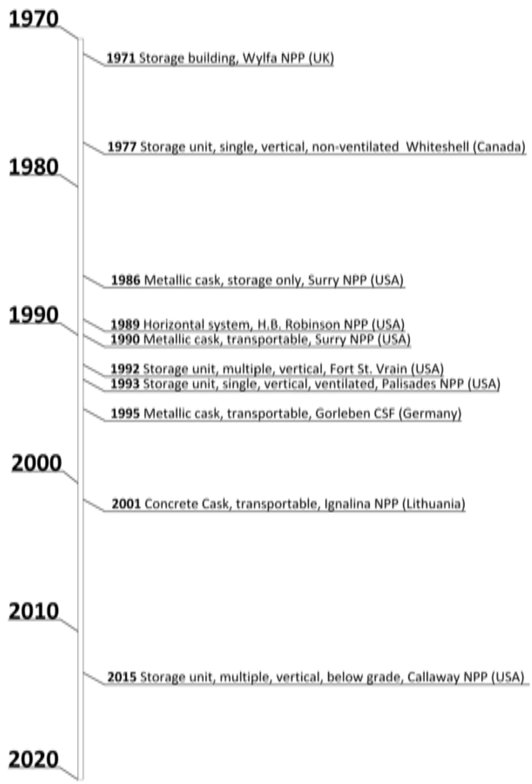


FIG. 12. Timeline of first deployment of each kind of dry storage technology.

metal casks were put into service around the mid-1980s. Around ten years later, vertical storage units were combined to produce larger units (MACSTOR: Modular Air-Cooled STORage) and concrete casks were introduced to the market. Ventilated vertical storage units became available in the 1990s (1993–1996 in the USA), enabling much higher heat loads than the first versions. Recently, in 2015, vertical storage units below ground level were introduced, providing additional protection against natural or human-made events.

Distribution of spent fuel inventory in the different types of dry storage systems as of the 2019 reporting date is shown in Fig. 13.

The relative distribution of spent fuel inventory in different dry storage systems by regions is shown in Fig. 14. In Latin America and Asia and Pacific, dry storage is predominantly used for CANDU fuels, which is why use is dominated by vertical storage units; either single units (concrete silos) or multiple units, such as the MACSTOR. Metallic casks are used for LWR fuel in Japan.

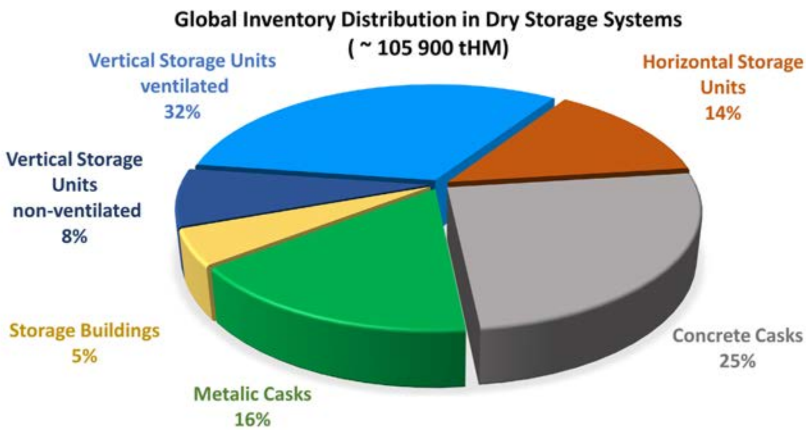


FIG. 13. Distribution of global dry inventory, 2019.

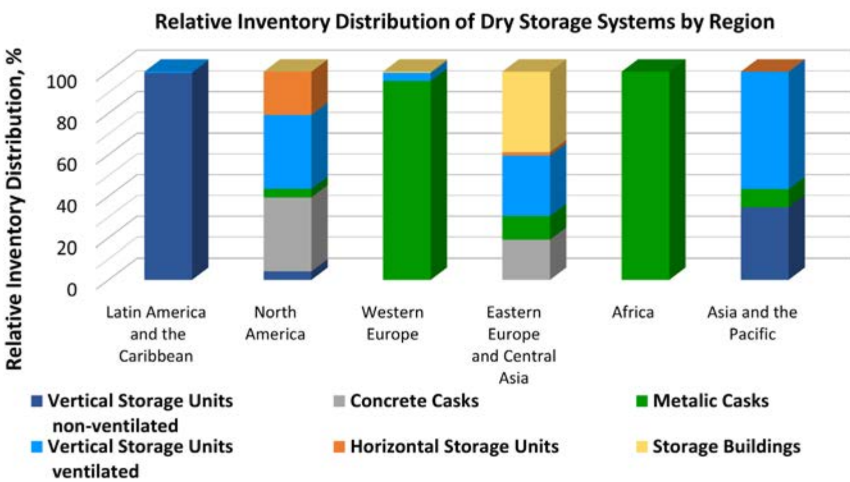


FIG. 14. Use of different dry storage systems by region, 2019.

In Western Europe, storage within metallic DPCs is the preferred approach. The decision to adopt metallic DPCs is related to regulatory requirements and the ability to both store and transport fuel within the same casks.

A significant portion of dry stored spent fuel in Eastern Europe and Central Asia is held in storage buildings at the Paks Modular Vault Dry Store (MVDS) in Hungary and the Mining Chemical Complex (MCC) in the Russian Federation. Storage technology choices between the other Eastern European countries vary depending on several factors including available funding, fuel cycle policy and fuel type.

In North America, a wide range of technologies are in use. In the USA, the choice of a dry storage system used at an NPP site is made by the utility that is managing it. This choice is dependent on many factors including fuel type, date of installation, site conditions and future transport considerations; more than one type of design can often be found on the same site. In Canada, a variety of designs are in use for storage of CANDU fuel including concrete casks and vertical storage units.

Currently available dry storage technologies are described in the following subchapters.

3.2.1. Dry storage casks (metal and concrete)

A dry storage cask provides containment of the spent fuel using physical barriers, which may include a metal body or a concrete body with a metal liner. Although multiple designs are available, with some examples presented in Fig. 15, the following features are common to all:

FIG. 15. Examples of different cask type at Idaho National Laboratory, USA.

- Spent fuel assemblies are maintained in a fixed position either using an integral basket for a bare fuel system or being held within a separate metal canister;
- The cask is sealed using either a bolted closure with seals, or welding, depending on the design;
- Decay heat is removed from the fuel by conduction, radiation and natural convection to the surrounding environment;
- Radiological shielding is provided by the cask body.

In addition to storage, some casks can also be used for transport of spent fuel and other radioactive materials.

Casks are either stored inside a building or placed outside on a concrete pad, depending on national regulations and environmental conditions (i.e. marine, arid, humid). Other factors that influence cask placement include the technology used, national security requirements and the location of the facility. A cask storage facility may include dedicated equipment for cask handling, fuel handling, decontamination, radiation protection monitoring and leak tightness monitoring. Casks may or may not be, depending on regulatory requirements, continuously monitored for leak tightness, dose rate and temperature. If not continuously monitored, casks are regularly inspected.

During the design stages of a cask storage facility, the infrastructure required to manage the casks over the longer term needs to be taken into consideration. In particular, any maintenance or contingency that is dependent on AR services (such as undertaking replacement of the cask seals if required) will be difficult if reactor infrastructure is reduced or eliminated following decommissioning of the reactor.

3.2.1.1. Metal casks

Metal casks are either loaded with canisterized fuel or fitted with an integral basket facilitating fuel assembly subcritical geometry and decay heat transfer from the spent fuel to the cask body as indicated in Fig. 16.

Metal casks are thick walled containers; the structural materials or main body may be forged steel, nodular cast iron, or a steel/lead sandwich structure. The metal casks' outer surface may be painted or stainless steel and allows decay heat to be removed through mainly conduction and convection, and also by radiation. The main body provides the gamma shielding. Designs generally include additional neutron shielding and there are two options currently in use: polymer compounds or water compartments to which a propylene glycol additive is eventually added. Various polymers are used: high density polyethylene rods or layers made with thermoset based compounds (for example, polyester or epoxy).

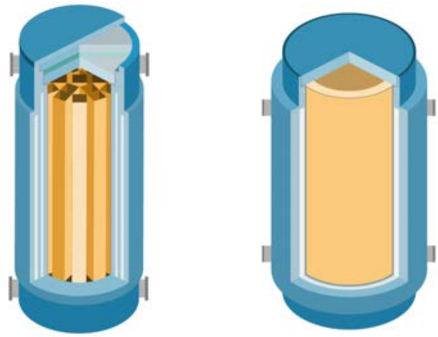


FIG. 16. Interior structure of metal casks for bare fuel (left) and canisterized fuel (right).

Metal casks usually have a bolted double lid closure system including metal seals monitored for leak tightness. A scheme of metal cask components is shown in Fig. 17.

Metal casks are usually transferred directly to the storage site from the fuel loading area. Some metal casks are DPCs designed and licensed for both storage and off-site transportation. In a transport configuration, the cask includes top and bottom shock absorbers (also known as impact limiters) for compliance with safety requirements under transport accident conditions; some designs also have additional shock absorbers around the cask body. This configuration is sometimes used on-site to transfer the cask from the fuel loading station to the storage facility. Spent fuel assemblies are loaded vertically into casks, which are often stored in a vertical position, but some metal casks are stored horizontally (for example at Fukushima Daiichi NPP, Japan, Fig. 18, and Koeberg NPP, South Africa, Fig. 19).

Horizontal storage of DPCs in concrete modules was also used as a temporary solution during construction of the on-site storage facilities in Germany (Fig. 20).

Metal casks are used for spent fuel storage in a number of countries such as Belgium, Czech Republic, Germany, Japan, Kazakhstan, Lithuania, South Africa, Spain, Switzerland and USA.

3.2.1.2. Concrete casks

Concrete casks are used for storage and, in some cases, transport of spent fuel. Structural strength and radiological shielding are provided by reinforced regular or high density concrete. They may use a painted metal liner on the outside and another one in the cask cavity to contain spent fuel. Heat transfer may take place solely by conduction through the concrete structure. Therefore, this type of

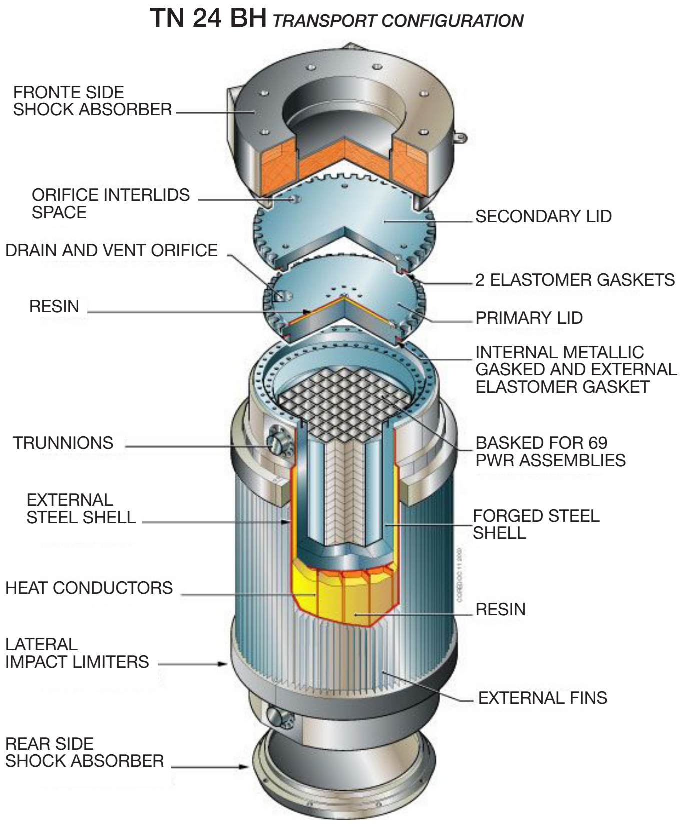


FIG. 17. Main components of a metal cask for dry storage of spent fuel assemblies (courtesy of Orano TN International).

FIG. 18. Temporary dry cask storage facility in Tokyo Electric Power Company (TEPCO) Fukushima Daiichi NPP.

FIG. 19. Horizontal storage at Koeberg, South Africa (courtesy of Gesellschaft für Nuklear-Service).

FIG. 20. Temporary horizontal storage in Germany (courtesy of Gesellschaft für Nuklear-Service).

cask has more thermal limitations than those systems using natural convection air passages. Concrete casks can use either a single or double lid closure system that, depending on the design, can be welded or bolted closed and then tested for leak tightness. Concrete cask systems may or may not be monitored for leak tightness, depending on regulatory requirements. Figure 21 shows a concrete cask.

Spent fuel is vertically loaded directly into the basket of the concrete cask in the fuel loading station and then transferred to the storage facility. The concrete casks are stored in a vertical orientation.

Concrete casks are used in a number of countries such as Bulgaria, Canada (Fig. 22) and Lithuania (Fig. 23). Gesellschaft für Nuklear-Service has developed the CONSTOR concrete cask, which is available with and without cooling fins

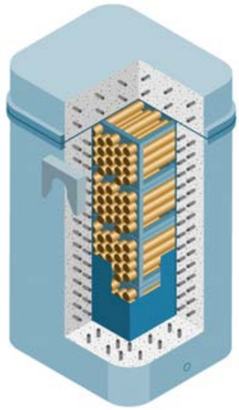


FIG. 21. Internal and external structure of a concrete cask.

FIG. 22. Ontario Power Generation's concrete dry storage container, Canada.

and is transportable (Fig. 24). Pakistan has developed a domestic design. Ontario Power Generation's concrete dry storage container is also designed for off-site transport.

Distribution of the global inventory of spent fuel stored in dry storage casks (metal and concrete) by region and by country is shown in Figs 25 and 26, respectively. By the end of 2019, dry cask storage facilities were available in Belgium, Bulgaria, Canada, Czech Republic, Germany, Japan, Kazakhstan, Lithuania, Russian Federation, South Africa, Spain, Switzerland and USA using a variety of designs. Additionally, further cask facilities are under licensing and construction in Japan and Spain.

FIG. 23. Dry storage in CONSTOR concrete casks NPP Ignalina, Lithuania (courtesy of State Enterprise Ignalina Nuclear Power Plant).

FIG. 24. CONSTOR casks, Gesellschaft für Nuklear-Service, Germany.

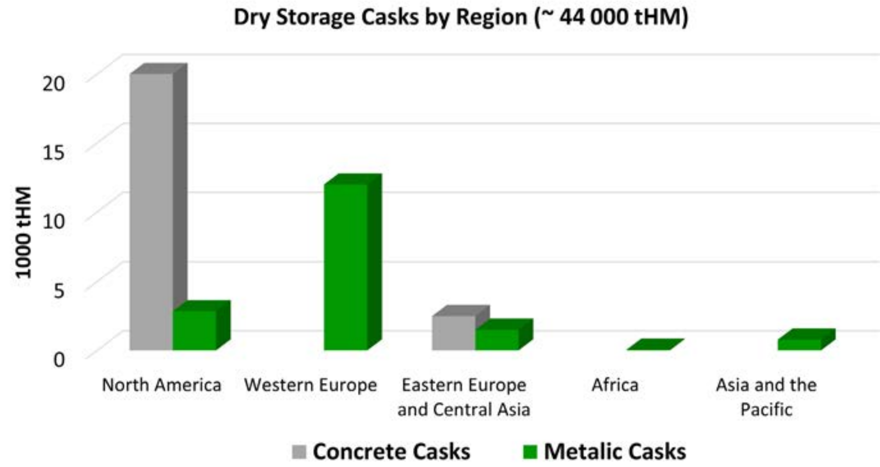


FIG. 25. Overview of dry storage in metal and concrete casks by region, 2019.

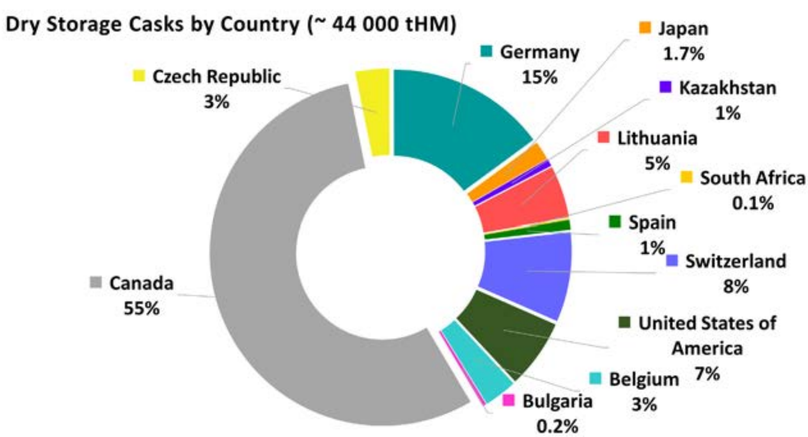


FIG. 26. Overview of the distribution of the global inventory of spent fuel stored in dry storage casks by country, 2019.

3.2.2. Dry storage units (vertical and horizontal)

Dry storage units are monolithic or modular reinforced concrete structures. The concrete provides shielding, while containment is provided by either an integral inner metal liner that can be sealed after fuel loading or by a separate sealed metal canister.

More than the half of the spent fuel inventory in storage units is in USA (Fig. 27). Brazil, Mexico, Slovakia, Slovenia, Spain, Switzerland, Ukraine and

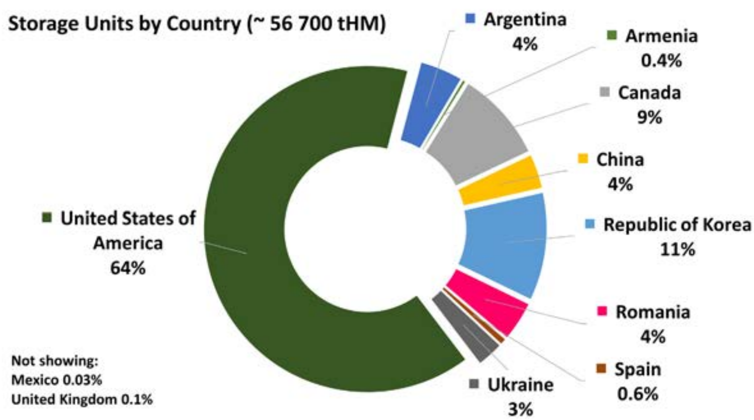


FIG. 27. Overview of the distribution of the global inventory of spent fuel stored in dry storage units by country, 2019.

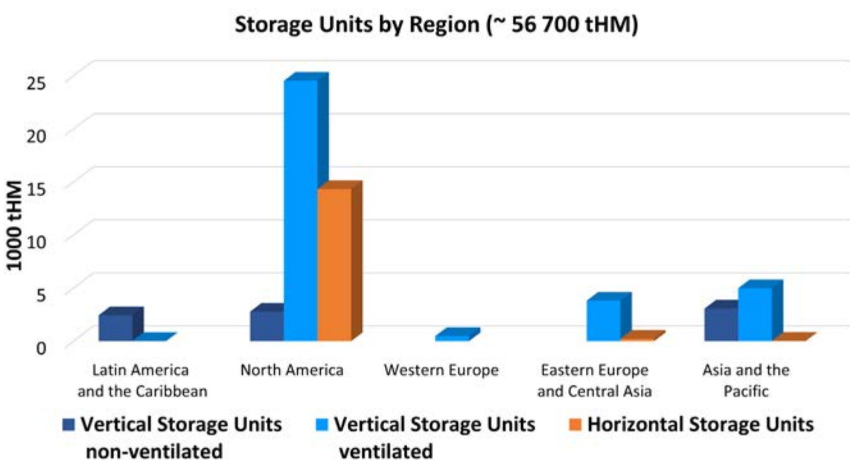


FIG. 28. Regional overview of spent fuel in dry storage units, 2019.

the UK are all at different stages of introducing storage units as part of their storage strategies.

Dry storage units can be arranged either in a vertical or horizontal configuration. Figure 28 provides an overview of the spent fuel inventory distribution between vertical ventilated, vertical non-ventilated and horizontal storage units by region. The horizontal configuration is mainly distributed in North America.

3.2.2.1. Vertical storage units

A typical early example of a vertical storage unit (sometimes referred to as silos) is the CANSTOR (CANdu STORage) module designed by Atomic Energy of Canada. These units were built on-site using regular reinforced concrete and fitted with a steel inner liner. Spent fuel is loaded into sealed baskets and transferred to the storage unit using a shielded transfer cask that is then loaded vertically into the system. A closure shield plug is placed and welded to the inner liner to provide additional containment once loading operations are complete. Figure 29 shows a non-ventilated vertical storage unit. This system is also used at Wolsong (Republic of Korea), and a similar arrangement is used at the Embalse NPP in Argentina (Fig. 30).

The MACSTOR modular structure is an array of storage cylinders — similar to the CANSTOR system — assembled together in a single monolithic

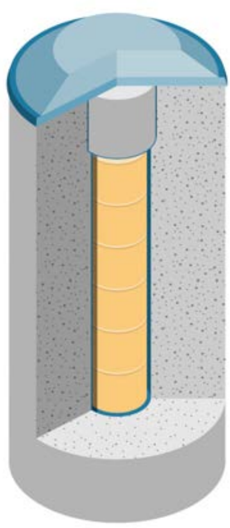


FIG. 29. Cross-section of a non-ventilated vertical storage unit.

FIG. 30. Dry storage at Embalse NPP, Argentina (courtesy of Comisión Nacional de Energía Atómica/CNEA).

structure. MACSTOR, distributed by Candu Energy Inc., was developed for LWR spent fuel but has been used only for CANDU fuel storage to date. The module has large air inlets and outlets, laid out as labyrinths for shielding, on each side of the structure as indicated in Fig. 31. The cooling air, driven by natural convection, enters through the bottom air inlets and exits through the top air outlets. The storage cylinders penetrate the module's top slab and are installed hanging inside the module. They are laterally restrained at their base by two seismic restraints, anchored in the module's floor. The fuel may be loaded into the storage cylinders in sealed metal baskets, depending on the fuel type and the particular storage system (see scheme in Fig. 32). The sealed metal baskets may be licensed for transportation as part of a transportation package. Modules are deployed at Gentilly-2 (Canada), Qinshan (China), Wolsong (Republic of Korea) and Cernavoda (Romania).

Ventilated vertical storage units are capable of housing LWR fuel and/or high level waste (HLW) in a seal-welded dual purpose canister (Fig. 33). The vertical storage cask (VSC) developed by Sierra Nuclear, MAGNASTOR (Nuclear Assurance Corporation, NAC Intl.) (Fig. 34) and HI-STORM (Holtec International Storage Module) is an example of ventilated vertical storage units. Air inlets at the bottom of the unit and an outlet at the top ensure sufficient cooling by natural convection. These types of storage units have been mainly deployed in Ukraine and USA.

The other example of a silo type is Holtec International's underground storage facility (HI-STORM UMAX), which is described in Appendix I.

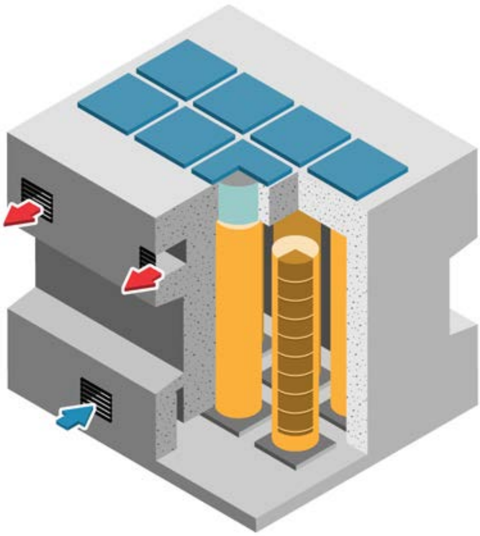


FIG. 31. Cut-away view of a vertical, multiple storage unit.

FIG. 32. MACSTOR 400 cross-section (courtesy of Korea Hydro & Nuclear Power Co., Ltd., Republic of Korea).

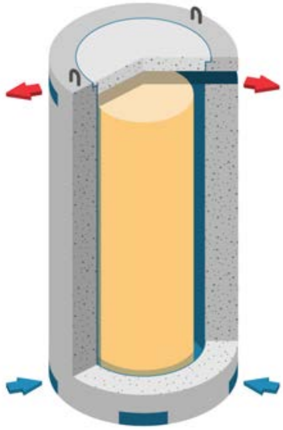


FIG. 33. Cut-away view of a ventilated vertical storage unit.

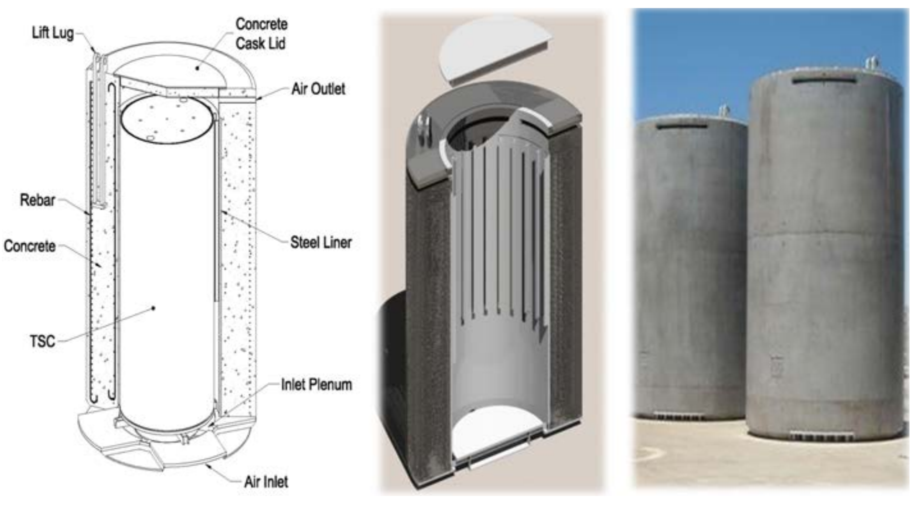


FIG. 34. Vertical storage unit (MAGNASTOR, NAC) system with a canister inside.

3.2.2.2. Horizontal storage units

Horizontal units use the same concept as the vertical monolithic units, just in a different orientation. These storage units can be arranged in one or two levels and can be monitored for dose rate and leak tightness. A diagram of the system is shown in Fig. 35. Orano TN's matrix horizontal storage module (Fig. 36) is an example of a two level unit, designed to reduce the storage footprint.

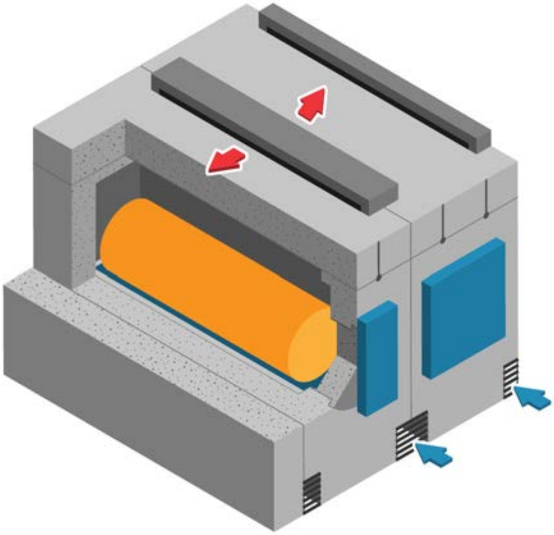


FIG. 35. Cut-away view of a horizontal multiple storage unit.

FIG. 36. Matrix system at Wolf Creek NPP (courtesy of Orano).

Spent fuel is loaded vertically into metal canisters which are welded shut and taken to the storage area inside a transfer cask. The canister is pushed out of the transfer cask in a horizontal orientation and placed inside the concrete storage module (Fig. 37).

FIG. 37. Loading the canister into a horizontal concrete module (Orano's NUclear HOrizontal Modular Storage system known as NUHOMS, TN Americas).

3.2.3. Storage buildings

Storage buildings for SNF (sometimes called vaults) typically consist of above- or below-ground reinforced concrete buildings containing arrays of storage cavities suitable for the containment of one or more fuel assemblies. Shielding is provided by the exterior structure. Heat removal is normally accomplished by the natural convection of air or gas over the exterior of the storage cavities and subsequently by discharging this air after monitoring.

Vaults are also modular, which facilitates incremental capacity extension, separated shielding and containment functions and the capability for containment monitoring. They are housed in a building with the associated infrastructure (cranes, ventilation, etc.) as indicated in Fig. 38.

Spent fuel is received (either dry or wet) at a storage facility using transfer or transportation casks, depending on whether the facility is at the reactor site or not. The fuel is then removed from the transport casks, prepared for storage (e.g. dried) if needed, and placed into a metal storage tube (single fuel element) or a storage cylinder (single or multielement canister), which is vertically oriented and housed within a concrete storage cavity in the vault structure. The storage tubes or storage cylinders are sealed and are backfilled with an inert gas to improve heat transfer and prevent oxidation of the spent fuel while in storage. Some designs are fitted with connections to allow for continuous or periodical monitoring of fuel conditions and/or containment.

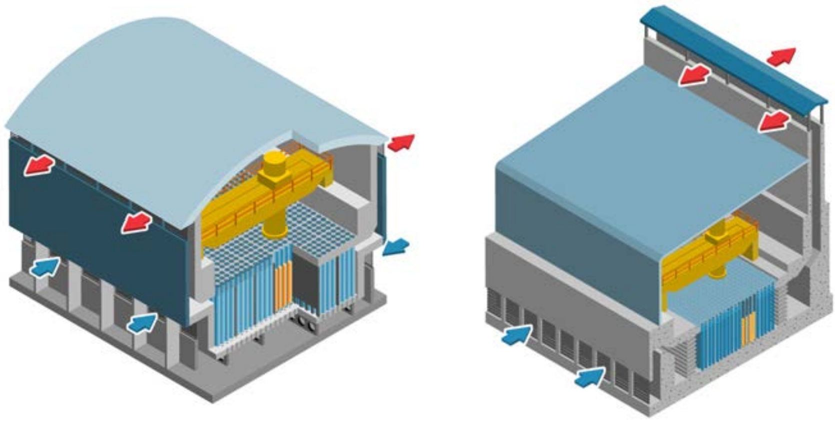


FIG. 38. Cross-section views of (left) storage building with canisterized fuel and (right) bare fuel.

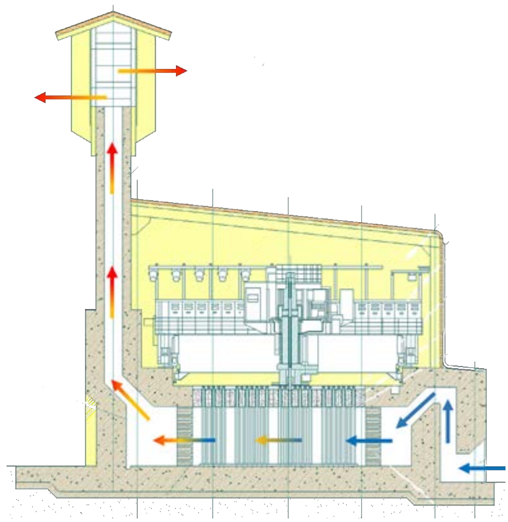


FIG. 39. Structure of the MVDS at Paks NPP Hungary.

Typical components of this type of storage facility are the vault modules, the fuel handling machine, the cask receiving area and the auxiliary facilities (areas for plant control, maintenance, services, offices, etc.). An example is the MVDS facility at Paks NPP (Hungary), shown in Figs 39–41.

Vaults using storage cylinders can receive the fuel already sealed in a canister, as at Fort St. Vrain MVDS (USA), or the fuel can be loaded into canisters

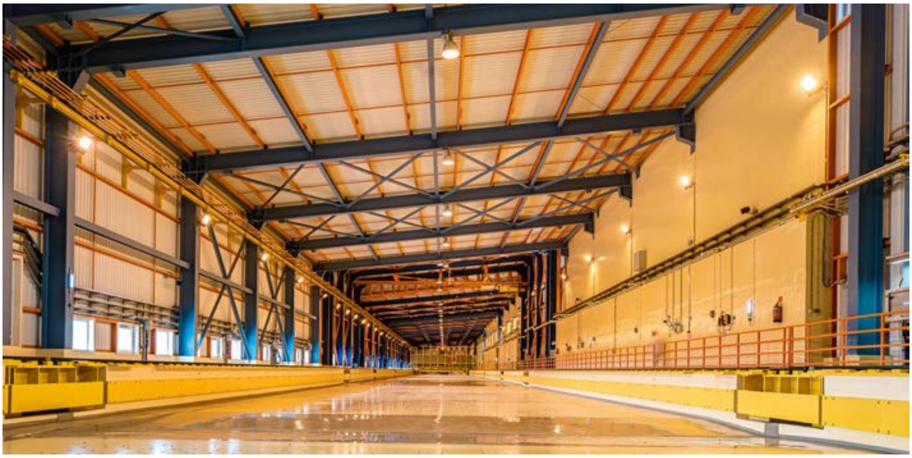


FIG. 40. Storage hall of MVDS at Paks NPP Hungary.

FIG. 41. Detailed view of the top of the storage tubes at Paks NPP Hungary.

in a hot cell at the storage facility, such as in the centralized dry storage facility at the MCC (Russian Federation) shown in Fig. 42. These types of vault facilities use a refuelling machine. The transfer of the filled canister into the storage cavity is performed either remotely (MCC) or with operator assistance (Fort St. Vrain).

About 8% of the spent fuel inventory stored in dry systems is contained in storage buildings, the majority of it at the MCC (Russian Federation), as shown in Fig. 43. One facility of this type is currently under construction in Slovakia.

FIG. 42. Zheleznogorsk Dry Storage Facility, Rosatom Mining Chemical Complex, Russian Federation.

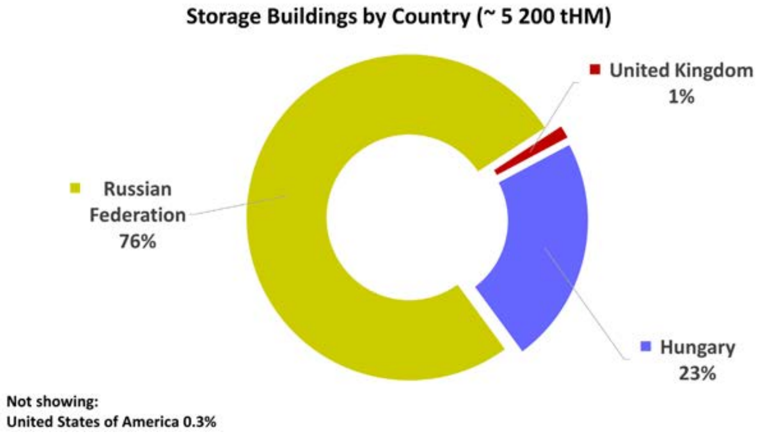


FIG. 43. Overview of the distribution of the global inventory of spent fuel stored in storage buildings by country, 2019.

4. SAFETY

Spent fuel storage facilities (wet or dry) contain a large amount of radioactivity and are regulated by the competent national authority. Safety considerations for all spent fuel storage operations are addressed in a series of international safety guidelines issued by the IAEA and various other international organizations and are used as the basis for appropriate national regulatory documents, some of which are listed in Appendix II. Each Member State can establish its national nuclear safety regulations on the basis of said regulatory documents. Together they form stringent nuclear safety and radiation protection criteria and regulations to meet the main safety objective of protecting people and the environment from harmful effects of ionizing radiation.

The IAEA Safety Standards provide the fundamental principles, requirements and recommendations to ensure nuclear safety. There are three tiers of publications:

— Safety Fundamentals establish the fundamental safety objective and principles of protection and safety;
— Safety Requirements set out the requirements that must be met to ensure protection of people and the environment now and in the future;
— Safety Guides provide recommendations and guidance on how to comply with the requirements.

Safety regulations and guides, which specify the principles, requirements and associated criteria for safety, are to be established or adopted by the national regulatory body, as is described in Requirement 32 of GSR Part 1 [17].

In accordance with the IAEA's Specific Safety Requirement SSR-4 Safety of Nuclear Fuel Cycle Facilities, Requirement 2 [18], the prime responsibility for the safety of a nuclear fuel cycle facility over its lifetime is allocated to the operating organization. This responsibility includes ensuring that the design meets all applicable safety requirements.

The main safety functions, which ensure that any nuclear fuel cycle facility is safely designed and operated, are given in IAEA SSR-4 [18]. These safety functions also ensure "that impacts on people and the environment are as low as reasonably achievable" [18]. These functions, as applied to the storage of SNF, are further elaborated in the IAEA's Specific Safety Guide SSG-15, Storage of Spent Nuclear Fuel [2] as follows:

(a) Containment of radionuclides;
(b) Criticality safety;

(c) Heat removal;[11]
(d) Radiation shielding;
(e) Retrievability.

An example of the safety functions in a dry metal cask design are shown in Fig. 44.

Though not specifically mentioned in IAEA SSR-4 [18], retrievability is included in IAEA SSG-15 (Rev. 1) [2], where it is clearly stated that "[t]he intention in storing spent fuel is that it can be retrieved for reprocessing or processing and/or disposal at a later time". For fuels stored as bare assemblies, maintaining the structural integrity of the fuel and cladding satisfies the retrievability function. Consideration also has to be given to satisfying the retrievability function by ensuring retrievability of the package. When the necessary safety functions are provided by the package, this approach can ensure safety functions are maintained in the event of some fuel degradation.

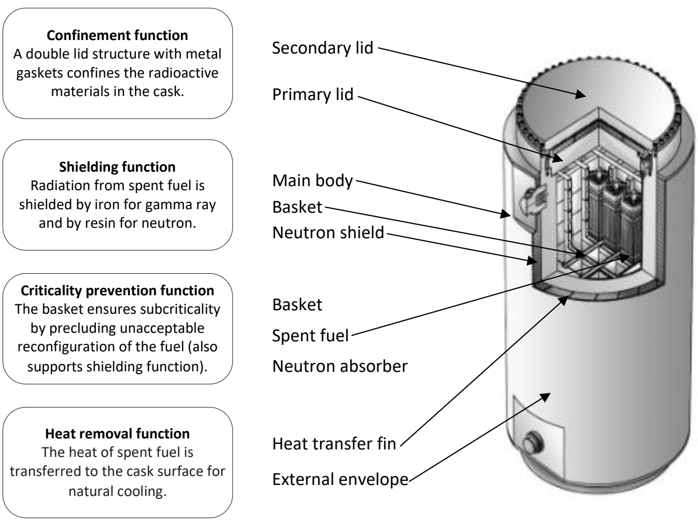


FIG. 44. Concept of metal cask and safety functions for spent fuel storage (Reproduced with permission from Saegusa, T. (2015). Basis of Spent Nuclear Fuel Storage, ERC Publishing Co., Ltd.).

[11] Heat removal is important because it influences corrosion and other mechanical properties that are relied upon to maintain fuel geometry, which is necessary to ensure both shielding and subcriticality.

As an example of different methods that may be acceptable for retrievability, the United States Nuclear Regulatory Commission Standard Review Plan for Spent Fuel Dry Storage Systems and Facilities [19], which addresses spent fuel retrievability in storage applications, allows for retrievability to be satisfied by any of the three options below, either individually or in combination, as appropriate:

— “Remove individual or canned[12] SNF assemblies from wet or dry storage;
— Remove a canister loaded with SNF assemblies from a storage cask or overpack;
— Remove a cask loaded with SNF assemblies from the storage location” [19].

This provides options for maintaining retrievability, as well as confining fuel materials to a known geometry for shielding and criticality calculations, even if fuel or cladding integrity becomes compromised. It also provides an option for transferring safety functions from the fuel and cladding to components that can be more easily monitored and inspected and, if needed, repaired or replaced.

The safe operation and maintenance of spent fuel storage facilities, as for other engineered systems, depends in part on adequate design and construction. Paragraph 1.3 of SSG-15 [2] states that “[t]he safety of a spent fuel storage facility, and of the spent fuel stored within it, is ensured by appropriate confinement of the radionuclides involved, maintaining subcriticality, heat removal, radiation shielding and retrievability of the spent fuel or spent fuel packages”. To achieve these objectives, the design of spent fuel storage facilities has to incorporate features to maintain fuel subcriticality, to remove spent fuel decay heat, to provide for radiation protection and to maintain containment over the anticipated lifetime of the facilities as specified in the design specifications. These objectives have to be met in all anticipated operational occurrences and DBAs in accordance with the design basis as approved by the regulatory body. The safety analysis report for the spent fuel storage facility is prepared to document how these requirements are met.

As stated in Requirement 4 of GSR Part 5, “[t]he operator shall carry out safety assessments and shall develop a safety case, and shall ensure that the necessary activities for siting, design, construction, commissioning, operation, shutdown and decommissioning are carried out in compliance with legal and regulatory requirements” [1]. In accordance with para. 4.3 of SSR-4 [18], the operating organization of a spent fuel storage facility “…shall prepare a detailed demonstration of safety, which shall include an adequate safety analysis, at each

[12] ‘Canned’ is a term used mainly in the USA referring to fuel placed inside a ‘damaged spent fuel can’, the function of which is to allow handling of damaged fuel. A ‘damaged spent fuel can’ is given credit for maintaining geometry.

stage in the lifetime of the facility. The safety analysis at each stage shall include an adequate demonstration of how the operating organization intends to discharge its responsibility for safety at all subsequent stages in the lifetime of the nuclear fuel cycle facility" [18].

4.1. GENERIC SPENT FUEL STORAGE DESIGN SAFETY CONSIDERATIONS

Safety requirements related to the design of spent fuel storage facilities are established in Section 6 of SSR-4 [18]. Recommendations to meet the applicable requirements for these facilities are provided in IAEA SSG-15 (Rev. 1) [2], and specific examples on the lessons learned from spent fuel storage operation are shown in the IAEA-TECDOC-1725 [13].

Typically, the fundamental design requirements will address such considerations as the need to ensure an adequate degree of redundancy, diversity and reliability, and the need to ensure that any failures which might occur are limited in scope and to the fullest extent possible.

Typical considerations related to spent fuel that are to be addressed in a facility's safety analysis report include the following:

— Design basis fuel assemblies:
  - Physical description (form, composition, materials, mass, etc.);
  - Initial enrichment;
  - Burnup and burnup history;
  - Minimum cooling period;
  - Isotopic composition at time of storage;
  - Radiation fields at time of storage;
  - Reactivity at time of storage;
  - Decay heat production.

— Arrangements for damaged fuel or fuel outside specifications.

— Fuel inventory:
  - Number of assemblies per storage unit;
  - Total number of assemblies.

— Anticipated maximum storage duration.

The isotopic characterization of individual assemblies is necessary to accurately determine radiological and decay heat conditions, and several validated and verified computer codes are available for such characterization.

The decision to introduce higher burnup[13] and/or MOX fuel impacts the full fuel cycle, including front end and reactor operations. Higher burnup and MOX fuels have significant effects on spent fuel storage and transportation systems as additional heat dissipation and shielding capabilities are required. For higher burnup fuel, these are partially compensated by the reduction of the amount of spent fuel that is generated.

The increased heat and gamma radiation of these fuels can be accommodated by additional cooling time. MOX fuels also have a higher neutron activity due to their minor actinide content; the increased neutron radiation requires the neutron and gamma contributions to the overall dose rate to be accounted for when selecting a transport or storage cask.

Higher burnup fuels will typically have a higher initial enrichment, which needs to be considered in the design and criticality safety analysis. Criticality control of higher burnup and MOX fuels can be achieved by a number of design parameters,[14] with burnup credit (where permitted) likely to be the most effective means of demonstrating criticality safety in licensing. Burnup credit assumptions are being used more often in criticality analysis, but may require physical measuring of the fuel assemblies, calculations or a combination of approaches.

When burnup is increased, there are changes in the characteristics of nuclear fuel rods (described in Section 5.1.2.) that may affect their behaviour and that may impact their storage, transport and disposal.

Given these uncertainties, several national and international research and development programmes have investigated the technical concerns and provided data that are used to support the development of specific regulatory guidance [20–22]. Some countries have taken a different approach, for example limiting peak cladding temperatures, which can impose operational restrictions such as cask loading limits and longer wet storage periods [23].

The majority of LWR SNF generated in the future is expected to be in the higher burnup range. A quantity of higher burnup spent fuel is already stored in dry conditions, and the amount will continue to increase in the near term.

Loading of spent MOX fuel into suitable casks has been carried out with no evidence of difficulties. However, given the longer decay cooling time required (3–6 times longer), spent MOX assemblies are usually retained in the pool by utilities while uranium oxide (UOX) fuel is transferred to dry storage first.

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[13] Increasing fuel burnup is a means of reducing the number of refuelling outages for the same electricity production. Fuel burnups have been increasing in recent years. Different countries assign different reference values to the common term ‘high burnup fuel’; in this publication, the term ‘higher burnup’ is used as a generalization.

[14] Examples include the addition of neutron absorbers, moderator exclusion, moderator displacement and geometry control.

It is required (Requirement 10 of SSR-4 [18]) that the design of a spent fuel storage facility apply the concept of defence in depth. As indicated in para. 6.3 of SSG-15 [2] that “designs of spent fuel storage …should consist of relatively simple, preferably passive, inherently safe systems… [and] contain features to ensure that associated handling and storage operations are relatively straightforward”, the implementation of defence in depth will generally mean the use of multiple barriers to prevent or mitigate risks. These barriers may include the fuel matrix and cladding, with appropriate note taken of potential cladding failures and the fact that the retention of volatile materials and particulates by the fuel matrix is a function of the temperature and environment. Further containment barriers may include the pool boundary with its auxiliary systems, a container or storage tube in a vault storage facility or the liners, seals and other components of casks and silos.

Some details illustrating the general design considerations include the following:

— The spent fuel storage facility’s physical layout and arrangement needs to ensure maintenance of subcriticality during operational states and accident conditions through geometrically safe configurations (e.g. fuel baskets, storage racks and canisters). Any additional means required to ensure subcriticality, such as fixed neutron absorbers or the use of a credit for burnup to the extent allowed by the regulator, has to be specified in the design.
— Spent fuel storage facilities need to be designed with heat removal systems capable of cooling stored fuel from the first fuel assembly loading and need to be designed based upon the heat load of the anticipated maximum spent fuel inventory.
— The heat removal capability should be such that the temperature of all fuel (and fuel cladding) in a storage facility does not exceed the maximum temperature recommended or approved by the regulatory body for the type and condition of fuel to be stored.
— The design of heat removal systems for spent fuel storage facilities needs to include any appropriate provisions to maintain temperatures of systems, structures and components (SSCs) at acceptable limits.
— The design of spent fuel storage facilities needs to incorporate ALARA principles and provide for radiation protection of workers and the public in accordance with the principles and requirements described in the IAEA Basic Safety Standards for Radiation Protection [24] and its associated guide [25].
— Spent fuel storage and handling system designs need to provide for adequate and appropriate measures for containing radioactive materials to prevent

uncontrolled release to the environment. For example, storage building designs have to incorporate maintenance of sub-atmospheric pressures to prevent the spread of airborne radionuclides to other areas within the storage facility. Such areas may be provided with ventilation and filtration to maintain concentrations of airborne radionuclides at acceptable levels.

- Ageing management principles need to be applied to preserve the integrity of the spent fuel cladding and other safety significant SSCs against degradation, and to ensure they can be repaired or replaced as needed to ensure safety for the duration of the storage period.
- The facility needs to be designed to stand alone once the NPP is shut down, with capabilities to allow for storage system unloading, maintenance and/or repair.
- The ability to monitor the spent fuel containment and to detect containment failures has to be provided in the design. Periodic verification by observation or measurement can be implemented if continuous monitoring is not provided.
- The design of spent fuel storage systems need to incorporate independent containment barriers as required by the regulatory body.
- The design has to provide for appropriate collection, monitoring and treatment of surface water run-off.

4.2. SPECIFIC SPENT FUEL STORAGE DESIGN SAFETY CONSIDERATIONS

Although many safety considerations are applicable to all types of spent fuel storage facilities, there are some design specific safety considerations applicable only to wet or dry storage facilities; these are provided in Appendix I of SSG-15 (Rev. 1) [2]. Some key points are discussed below.

4.2.1. Wet storage

As indicated in para. 6.68 of IAEA SSR-4 [18] for spent fuel pools, a subcriticality design measure using passive features (such as prescribed spacing in racks) is preferred to one using active features (such as soluble neutron poisons). Soluble neutron poisons may be used in preference where there is a verification requirement with an appropriately justified frequency, if acceptable to the regulatory body.

In wet storage facilities, pool water boiling might be considered in accidental situations, but even in these cases, specific allowances need to be provided for the change in water/moderator density.

Some specific considerations based on best practices for pool layout and structure include [2]:

— Cooling water retention boundaries, including the pool structure, need to be designed to withstand operational states and accident conditions — in particular, impacts from collisions or dropped loads — without significant leakage of pool water.
— The water level has to be maintained to provide the required degree of shielding. Over-raising of fuel or other components needs to be prevented.
— The design needs to provide for detecting leakage and implementing appropriate repairs.
— Pools need to be designed to exclude piping, penetrations or other equipment or features that could inadvertently lower the pool water below the minimum operating level (e.g. penetrations below the minimum water level, piping and equipment that could act as a siphon).
— Pool water makeup systems have to be able to compensate for all potential losses to maintain water level within prescribed limits.
— Where sluiceways are used for pool connections, their design needs to afford confinement of water and detection, collection and removal of leakage. The gates should be designed to withstand anticipated water pressures.
— Protection against overfilling with water of the storage pool is to be provided.
— Buoyancy and shielding need to be considered in the design of equipment and tools, for example hollow handling tools for use under water designed to fill with water upon submergence and drain upon removal.
— Pools are to be provided with the necessary illumination equipment as well as underwater lighting and their replacement. The materials used in underwater lighting have to be compatible with the pool environment and not introduce any impurities into the pool water.
— Heat removal systems need to assure that no temperature limit is exceeded and that during normal operation and anticipated operational occurrences, the bulk temperature of the pool water remains within prescribed limits.
— Structural materials have to be compatible with the pool water or be effectively protected against undue degradation or corrosion. The storage structures or containers ought not to introduce any impurities into the pool water.
— Any equipment exposed to or in contact with pool water ought to be easy to decontaminate, and the requirements for decontamination need to be considered during the materials specification stage of the equipment.

The transparency of water required for handling operations in the pool below the waterline needs to be maintained and the chemistry conditions kept within the parameters required for fuel cladding, pool structure and equipment protection. Where lubricants are required for handling systems and equipment, their potential leak paths into the pool water need to be precluded.

While it is not explicitly stated in SSG-15 (Rev. 1) [2] that all new spent fuel pools are to be housed within a building, a recommendation to do so can strongly be inferred from the design considerations to be met.

The radioactivity of the water needs to be controlled to levels ALARA to permit timely detection of failed fuel, limit contamination of equipment and protect operators.

4.2.2. Dry storage

Dry storage systems provide the same safety functions as wet systems but without the reliance on water for cooling and shielding. Shielding is provided by the cask body or overpack or, in some cases, a shielded vault or cell. Radionuclide confinement is provided by the dry storage system boundary. The system boundary may also play a role in criticality safety by precluding the introduction of a moderator.

Some specific considerations for dry storage systems:

- For concrete storage overpacks with metal liners on the inside, the design needs to prevent the accumulation of water between the liner and the concrete overpack. The structure is to be provided with drainage.
- If stacking of the fuel baskets (see Fig. 32, MACSTOR) is proposed, the mechanical structure has to be designed to support the mass of other fully loaded baskets without structural deformity. Static, impact and seismic loads are to be considered.
- The foundation of the storage unit area needs to withstand the full load of the storage component and the handling equipment without excessive settling.
- Access needs to be controlled to limit exposures in accordance with ALARA principles (including ‘sky shine’ and the reflection of radiation).
- To the maximum practical extent, systems for cooling spent fuel ought to be passive and require minimal maintenance. The system needs to ensure sufficient transfer of residual heat to the surroundings even during adverse weather conditions.
- Fuel assemblies and the cask or canister cavity need to be adequately dried and inerted to protect the fuel integrity [12] and reduce degradation of the fuel cladding and the cask or canister internals in the long term. The design of the storage system needs to include provisions for monitoring and maintaining the gas medium necessary for the integrity of the stored spent fuel.

— The design of dry storage facilities ought to address the risk associated with the introduction of a moderator. This can be achieved by demonstrating, in a form acceptable to the regulator, that the consequence is acceptable and/or by precluding its introduction.
— The design of casks has to include provisions for lifting and handling, capable of withstanding potential structural challenges over its entire lifetime.
— Dry storage systems need to be designed to facilitate necessary inspections and monitoring required by the AMP.
— After the storage period, transport of any transportable system components has to comply with the applicable regulations at that point in time.

4.3. SAFETY ASSESSMENT

In general, 'safety assessment' is the assessment of all aspects of a practice that are relevant to protection and safety [26]. Safety assessment is the "[a]ssessment of all aspects of a practice that are relevant to protection and safety; for an authorized facility, this includes siting, design and operation of the facility" [4]. It is carried out systematically throughout the lifetime of the facility or activity to ensure that all the relevant safety requirements are met by the proposed (or actual) design [1].

The safety assessments are to be carried out and documented by the organization responsible for operating the facility or conducting the activity, are to be independently verified and are to be submitted to the regulatory body as part of the licensing or authorization process, as outlined in para. 1.2 of GSR-4 (Rev. 1) [26] and stated in GSR Part 5, Requirement 4 [1].

GSR Part 4 (Rev. 1) [26] establishes 24 requirements of safety assessments to be fulfilled. Recommended overall approach to safety assessment is given in GSG-3 [27] and includes the following key components:

— "Specification of the context for the assessment;
— Description of the predisposal waste management facility or activity and the waste;
— Development and justification of scenarios;
— Formulation of models and identification of data needs;
— Performance of calculations and evaluation of results;
— Analysis of safety measures and engineering aspects, and comparison with safety criteria;
— Independent verification of the results;
— Review and modification of the assessment, if necessary (i.e. iteration)" [27].

Additional guidance on safety assessment and the safety case for the storage of spent fuel is given in Chapter 5 of Ref. [2].

Safety assessment is a complex and iterative process which includes, but is not limited to, the safety analysis as one of the essential elements of the process. As described in Ref. [28], "[s]afety analysis is an analytical study, undertaken to demonstrate that the facility design meets safety and regulatory requirements and that the design is based on the application of sound engineering practices, research and feedback from operating experience…Systematic and recognized methods of deterministic analysis are required to be used for nuclear fuel cycle facilities, complemented by probabilistic assessments where appropriate, in accordance with a graded approach".

The design basis of a SNF storage facility is formed by the range of conditions for which a SNF storage facility is designed, according to established design criteria. As part of the safety analysis, various events and facility conditions caused by credible technical failures are considered and their potential consequences on safety are estimated. For this purpose, a range of postulated initiating events covering all facility states and their combinations are developed. Examples of selected postulated initiating events for a spent fuel storage facility may be found in the Appendix of SSR-4 [18]. A comprehensive list of postulated initiating events (internal phenomena) for consideration in a safety assessment is given in Annex VI of IAEA SSG-15 [2].

The scope of facility states considered in the design include operational states (normal operation and anticipated operational occurrences) and accident conditions (DBAs and design extension conditions (DECs)) as indicated in Fig. 45.

Design basis analysis is performed by systematic and recognized deterministic methods and may be complemented by probabilistic assessments where appropriate and in accordance with national regulatory requirements.

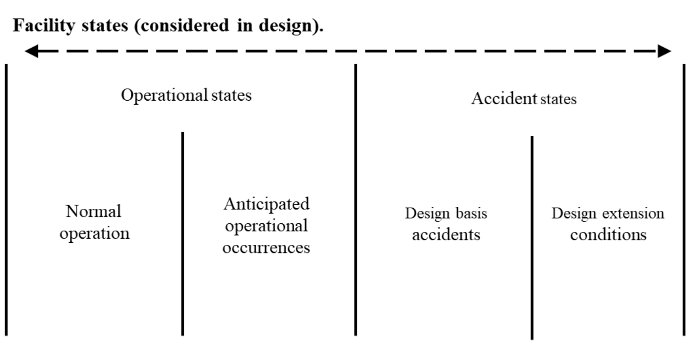

FIG. 45. Facility states considered in the design. Reproduced from Ref. [18].

4.3.1. Anticipated operational occurrences

Anticipated operational occurrences are defined as "[a] deviation of an operational process from normal operation that is expected to occur at least once during the operating lifetime of a facility but which, in view of appropriate design provisions, does not cause any significant damage to items important to safety or lead to accident conditions" [4].

Anticipated operational occurrences might occur in a spent fuel storage facility, for example, during the arrival and emplacement of spent fuel or necessary handling of the inventory during maintenance. Examples of events classed as anticipated operational occurrences relevant to spent fuel storage that can be analysed[15] are the following:

— Receipt and storage of fuel that is defective or out of specification;
— Incorrect loading of fuel;
— Heating and ventilation malfunction;
— Loss of electrical supply;
— Failure of heat removal system;
— Flow blockages;
— Faults in coolant or pool water circulation systems;
— Coolant, pool water or back fill gas composition that is out of specification;
— Coolant or pool water leak;
— Containment leak;
— Structural failures (e.g. failure of baskets or racks);
— Degradation of SSCs.

4.3.2. Design basis accidents

DBAs are accidents identified as having an infrequent probability of occurrence during the lifetime of the facility, if they are to occur at all. There are country specific differences in the regulations defining how the DBAs are derived.

Examples of DBAs are summarized in Appendix III. Note that this list is not exhaustive; a hazard analysis could identify other credible accidents, such as those resulting from operational errors, instrument failures, lightning and other occurrences. Post-accident recovery or retrievability of fuel, including damaged fuel, may require contingency arrangements such as overpacks or dry transfer systems that may be necessary if the spent fuel cannot be handled by normal means. If design features or other justifications assess a particular accident

[15] See SSG-15 Storage of Spent Fuel [2] for further information on anticipated operational occurrences.

condition as not credible, these are to be documented in the design documentation with adequate justification.

For all nuclear facilities, external hazards have to be taken into account when designing a spent fuel storage facility (wet or dry). These external hazards could be categorized in two different groups as:

— External hazards of natural origin: earthquake, flood, tornado, extreme atmospheric conditions, sandstorm, volcanic eruption;
— External hazards of human origin: hazards linked to transportation networks (air, rail, road, boat) and to industrial activities in the vicinity.

Lists of site conditions, processes and events related to external natural phenomena and to external human-induced phenomena for consideration in a safety assessment are given in Annex IV and Annex V of IAEA SSG-15 [2]. From these lists, it is apparent that the location of the facility will influence the potential external hazards to be considered. Additional margins need to be addressed to anticipate climate changes for facilities that will operate in the long term, as the ambient temperature plays an important role if natural convection is used to cool a facility. The rise of sea levels will affect the measures for flooding prevention and tsunami protection at sites that are located directly on the coast. Coastal sites may be more susceptible to chloride-induced corrosion mechanisms. Hence, the selection of the spent fuel storage site location will influence the potential hazards to be addressed. Different storage concepts do not have the same sensitivity to different external hazards; each has to be assessed using a specific safety analysis.

4.3.3. Design extension conditions

The concept of DECs was introduced following the Fukushima Daiichi accident in 2011. The DECs are used to identify additional accident scenarios that either are more severe than DBAs or involve additional failures so that they may be addressed in the design and to plan practicable provisions for their prevention or to mitigate their consequences (Requirement 21 of IAEA SSR-4 [18]).

DECs for spent fuel storage facilities cover accident situations with or without significant fuel degradation. The initiating events considered may include extreme earthquake, extreme flooding and other extreme natural phenomena, as well as the loss of electrical power, loss of cooling for an extended time and a combination of both. The list of DECs to be considered has to be defined specifically for each spent fuel storage facility. The analysis of DECs is used to identify additional accident scenarios and design additional safety measures (design, features, organizational provisions or equipment availability) to prevent or limit the consequences of accident situations or to assist emergency response.

In some cases, such as at a company level, it could be relevant to organize a task force that could intervene at different nuclear sites with specific means to help the local operator teams. In any case, a building sheltering the emergency management team, the intervention teams and all necessary infrastructures (depending on the technology used for storage e.g. for wet storage facilities: electricity generators, pumps, water reserves, etc.) has to be operational at each nuclear site. This building needs to resist hazards greater than or equal to those considered for the on-site facilities. The revisions in Safety Guide SSG-15 incorporated lessons learned from the Fukushima accident and “relate to the following main areas: (a) strengthening accident management; (b) protection against internal and external hazards; and (c) practical elimination of the possibility of conditions arising that could lead to early releases of radioactive material or to large releases of radioactive material” [2].

As described in IAEA SRS-102 [28], examples of causes that could result in DECs for nuclear fuel cycle facilities, including SNF storage, include the following:

— “Combination of anticipated operational occurrences or DBAs with a common cause failure of SSCs important to safety;
— Combination of SSCs and human failures that is considered significant in DBA analysis;
— Multiple failures of SSCs important to safety caused by rare extreme natural phenomena that are unlikely (but considered possible)” [28].

Further examples can be found in Annex IV of Ref. [28].

According to the safety assessment approach [27], all identified anticipated operational occurrences, DBAs and DECs in addition to normal operation are to be addressed in development and justification of scenarios for the purposes of the safety assessment and development of the safety case for the storage of spent fuel.

5. IMPACT OF AGEING ON SPENT FUEL AND SPENT FUEL STORAGE SYSTEMS

AMPs ensure that safety functions will be satisfied throughout the storage period. In most countries it is a requirement to have an AMP in place for spent fuel storage systems, ensuring that the effects of ageing are properly monitored and mitigated.[16] Any deviance from material behaviour used in the system design has to be identified and mitigated in a timely fashion to ensure safety functions are unaffected.

Since the operational periods of many NPPs have exceeded their original planned life, AMPs have been implemented to closely monitor their conditions and ensure the continued expected performance of SSCs. The development and implementation of such plans is a vital part of extending the operational life of reactors. As a result, there is a wealth of experience and data available from the implementation of AMPs for NPPs that can be applied to the development of AMPs for spent fuel storage systems [29].

Similarly, because spent fuel has to be stored until a path forward becomes available, it may be necessary to continue storing fuel beyond the original anticipated duration. Hence, the safety analysis and associated authorization has to consider methods for predicting, detecting and mitigating conditions that could compromise the performance of the spent fuel and the storage system. This approach will ensure the lifetime of these components can be effectively extended if needed or that there is sufficient lead time for the implementation of other options such as repackaging and relocation if they cannot be effectively repaired or replaced.

The first step of an AMP development is the identification of SSCs that are susceptible to degradation. The second step is then to characterize whether the SSCs are important to safety. It is important to bear in mind that, while an SSC may not be directly important to safety, its failure could affect the correct function of another SSC.

The core of any AMP is an understanding of the ageing related degradation mechanisms that have the potential to affect the SSCs of the spent fuel storage system. It allows for the implementation of solutions against ageing, corrective actions, repairs and eventual replacement of components. It is also important to review wider operating experiences as part of the development of further scientific and engineering knowledge to ensure that planned activities are optimal to achieving the required level of surveillance and reassurance. Further information for managing the ageing of nuclear fuel and dry storage facilities, etc. is provided in Refs [27–30].

The general principle of the management of ageing is illustrated in Fig. 46 and can be applied to any process where the safety functionality of SSCs could be compromised due to ageing.

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[16] 'Ageing management' is defined in the IAEA Safety Glossary as "Engineering, operations and maintenance actions to control within acceptable limits the ageing degradation of structures, systems and components" [4].

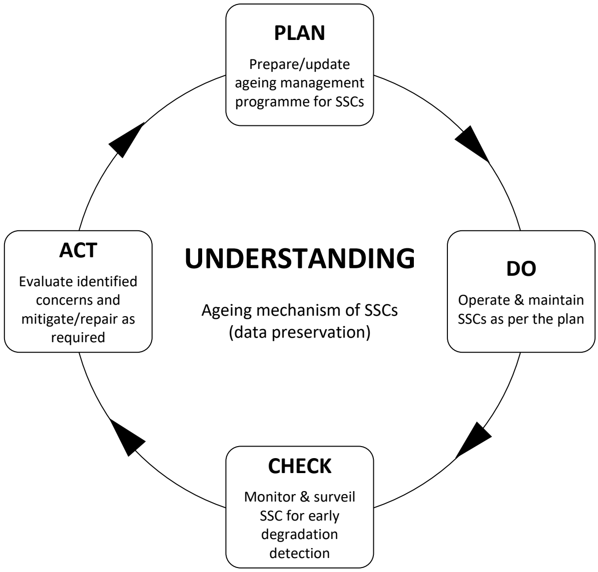

FIG. 46. Ageing management process for a spent fuel storage facility.

5.1. POTENTIAL DEGRADATION MECHANISMS AFFECTING STORAGE SYSTEMS AND SPENT FUEL

The behaviour of spent fuel storage systems and spent fuel during storage [30] is a function of material composition, manufacturing processes (for example final treatments such as heat treatments and coatings), the condition at the beginning of storage or when deployed (examples included residual stress, cracks and corrosion) and the operating environment (applied stress, temperature, atmosphere, etc.). The selection of materials used as fuel cladding, storage systems (racks, canisters, cranes, etc.) and materials of construction for buildings, pools, etc. are based on the following considerations:

— The operating environment (temperature of operation, radiation field, duration, chemistry, etc.);
— The knowledge of the degradation mechanisms that can influence individual materials or general degradation over time;
— Operating experience (how such materials have performed in the past).

5.1.1. Potential degradation mechanisms of storage systems, structures and components

The following section provides an overview of degradation mechanisms that can affect spent fuel storage systems. The section considers how these mechanisms can influence materials performance through using examples of materials in common use in spent fuel storage systems. Literature data for the performance of selected materials used in spent fuel storage systems is provided in Appendix IV.

5.1.1.1. Radiation damage

Materials in direct contact with or in the proximity of spent fuel will experience radiation damage over time. The net effect is that the mechanical properties of the material will be affected once a radiation dose threshold is met (sometimes known as radiation tolerance), and they will become more prone to failure. In the case of metals, they can absorb large neutron doses of 10^{19} n/cm^2 before they are severely impacted. For other materials such as polyvinylchloride, a gamma dose of 2×10^4 Gy is likely to result in a deterioration of properties. While most metals will not experience a sufficient cumulative dose during their lifetime to have a detrimental impact (see Appendix IV), consideration does need to be given to the impact of accumulated dose on materials for any life extensions or new duty. Cameras and electronics tend to have greater sensitivity to radiation. In the case of cameras, high definition digital cameras are now available at a relatively low cost. Depending upon the application and ease of access to replace them, it can be more cost effective to use and dispose of electronics, rather than using specialist radiation protected devices.

5.1.1.2. Temperature effects

Rapid increases or decreases in ambient temperature can affect material properties and ageing. Sometimes this is difficult to avoid, and such effects have to be taken into consideration in design. Thermal cycling or repeated shocking, however, needs to be avoided, particularly in concrete structures. Cool down is another period during which adverse conditions can arise, such as the formation of condensation that can act as an electrolyte to form a corrosion cell; this is a particular concern when combined with air pollutants, salt in coastal locations, stress or sensitization. The temperature ought to be maintained when the residual heat within the system cools down. Temperatures that are too low can also be detrimental as some material properties are temperature dependent, and some steels can suffer from brittle fracture. Hence low temperatures may limit fuel handling operations.

5.1.1.3. Operating environment

The choice of materials in design is influenced by the operating environment in which they are going to be used. Experience has shown that the operating environment can be harsher than envisaged, and the chosen material or plant item may require replacement sooner than planned (examples are provided in Refs [8, 13]). This experience emphasizes the need for routine monitoring and maintenance.

5.1.1.4. Potential degradation mechanisms of metals

Metals are widely used in spent fuel storage facilities and systems as structural materials, storage racks, handling machines, tools, casks, canisters, cask lifting equipment, cranes, etc. Their application and the mechanisms that can affect their performance have been extensively reported in Refs [12, 31–35]. The IAEA publication on the lessons learned from the spent fuel storage operation [13] provides further considerations in terms of learning from experience and how choices of metals in spent fuel storage have changed. For example, some metals have a greater affinity for adsorbing contamination, especially rust. This has led to the wide deployment of stainless steel, which is easier to decontaminate compared to other metals such as painted mild steel or cast iron. For very large items such as cask lifting beams, the choice between the use of stainless steel and painted cast iron is a balance between cost and the number of times it will be used versus dose uptake in decontaminating.

The following summarizes common degradation mechanisms for metals.

(a) Stress corrosion cracking

Stress corrosion cracking (SCC) can occur only if several conditions occur simultaneously [36]; that is, the metal has been sensitized, there is applied or residual stress, and an aggressor such as chloride ions is present. Notwithstanding this, such combinations of conditions are known to occur in some fuel cladding and dry storage system components.

(b) Electrochemical corrosion

Under a given set of conditions (temperature, aggressive chemicals, impurities, etc.) all metals are subject to electrochemical corrosion in one or more forms: general/uniform, pitting, crevice or dissimilar metals (galvanic).

(c) Brittle fracture

The potential for brittle fracture mainly concerns older large plant items made from cast iron or low carbon content steels (<0.5%) that operate outdoors with the potential to experience temperatures below 0°C. As the metal transitions from ductile to brittle, fracture can occur without first experiencing deformation if exposed to sufficient force. Components of concern are usually high strength and are thicker, such as beams, rails and large bearings.

(d) Microbial induced corrosion

As the name implies, microbial induced corrosion (MIC) is corrosion resulting from the activity of microbes (i.e. growth of a biofilm and creation of a localized environment that is detrimental to the metal they cover). There are many types of bacteria that reduce or oxidize elements and that flourish in given temperature ranges and conditions. Periodic sampling can indicate the type of bacteria present, but avoidance of growth is recommended; this can be achieved by limiting bacterial exposure to light, carbon, oxygen, nitrates, sulphates and phosphates.

(e) Fatigue

The design of spent fuel facilities and systems accounts for the number of proposed cycles that a particular piece of plant may perform during its projected life. For example, a building crane may be designed for a given number of cycles based on its foreseen duty. Extending operations can result in material failures if the extended duty for equipment and materials is not considered against the original design.

(f) Wear

Wear results from the interaction of material upon material and from external stressors such as vibration and misalignment. Wear is detected by routine plant inspections and the use of maintenance databases to record learning from experience and for trending.

5.1.1.5. Degradation mechanisms of concrete

Concrete is primarily used for shielding or in combination with steel reinforcement bars for the construction of buildings, pools, pads, overpacks, etc.

Good quality concrete is key to avoiding its degradation during application. In most applications, the ideal properties are high strength, resistance to weathering or volume change and low permeability (to avoid corrosion of the encased reinforcement bars). Learning from experience has led to the use of low water to cement ratios, specific aggregates (for example exclusion of chloride), techniques such as leaving the covers on for longer periods to increase moist curing durations, the amounts of reinforcement bar, ensuring the concrete is compacted around the reinforcement to avoid air gaps, and the depth of concrete between the reinforcement bar and the surface in contact with air.

Assuming that the concrete has been prepared properly and is crack free, then the main degradation mechanisms of concern are related to weathering. In particular, freeze–thaw cycling can lead to concrete jacking, thermal cycling, carbonation and adsorption of pollutants or salts. Carbonation through the slow diffusion of carbon dioxide into the concrete reduces the alkalinity of the concrete and eventually leads to attack of the encased reinforcement bar (usually noted by brown staining on the concrete surface). The loss of alkalinity or attack by pollutants is not considered an issue for concrete casks where the concrete is a filler between metal plates [9]. Pollutant or salt ingress will also eventually attack the reinforcement bar. A list of techniques for assessing ongoing concrete properties is provided in Ref. [37].

5.1.1.6. Degradation mechanisms of polymers

Polymers mainly find application as insulators for wires, neutron shielding materials, expansion joints and fillers. Polymer performance is very much related to its fundamental building blocks (parent monomers). Polymers degrade through a combination of radiation damage and thermal degradation, resulting in scission, cross linking and the release of small compounds (mainly hydrogen in the case of neutron absorbing materials). This results in changes to the polymers' physical properties, for example becoming brittle (with reduced neutron absorption capacity). Other less desirable compounds can also be released, such as silicon and hydrochloric acid [13], which can have implications for the plant and equipment. In the case of vinyl resins, which are highly crosslinked, thermal oxidation has been shown to be the dominant degradation mechanism.

5.1.1.7. Degradation mechanisms of composites

Composites find common use as neutron absorbing materials. Two types of composite material are in regular use:

— Sandwich: B_4C is sandwiched between two plates of aluminium;
— Metal matrix composites: B_4C is dispersed within the metal matrix.

Sandwich type absorbers have been reported to swell under some conditions (particularly at high temperatures in dry storage) and suffer corrosion of the sandwich ends (wet storage). Corrosion of the sandwich ends, while seen as undesirable, is beneficial in the control of radiolysis.

5.1.2. Spent fuel potential degradation mechanisms (wet and dry)

During irradiation, spent fuel undergoes several changes compared to its manufactured condition. These changes can be caused by the following:[17]

— Irradiation effects, which cause modifications to the fuel cladding and pellet microstructures or chemical composition;
— The production of fission gases;
— Thermal effects;
— Mechanical interactions between pellet and cladding or cladding and structural components;
— Internal attack of the fuel cladding by aggressive fission products;
— Corrosion or pick-up of chemical elements from the reactor coolant;
— Vibration, etc.

Some of the changes are shown for LWR fuel in Fig. 47. These initial storage properties can influence how the fuel will behave in subsequent fuel handling, storage and transport operations. It is therefore important to have a good understanding of whether these properties could affect spent fuel integrity and how they evolve with time to ensure that both fuel and cladding degradation are minimized or if provision needs to be made to ensure that safety functions are maintained. This is particularly applicable for degraded fuels.

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[17] In addition to the changes outlined, helium will accumulate in the fuel matrix due to alpha radiolysis. The effect of this helium accumulation is beyond the normal time frames for spent fuel storage of less than 100 years.

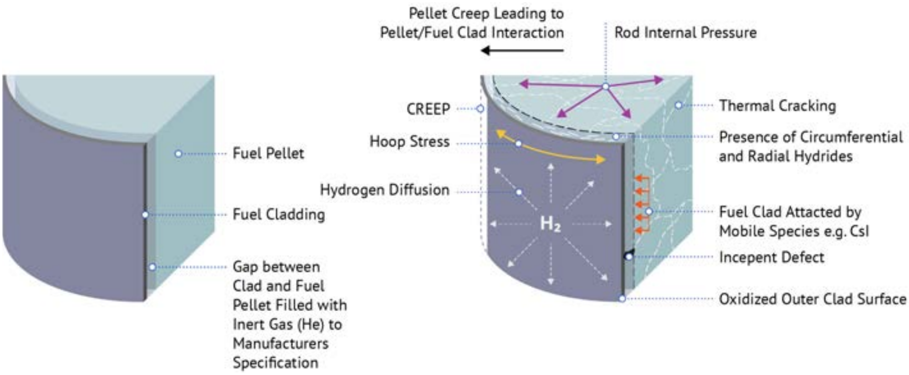

FIG. 47. Section through an LWR fuel pellet providing a comparison of the (left) before and after irradiation properties (right).

For spent fuel storage, the following degradation mechanisms have been identified:

— Uniform corrosion by the storage medium;
— Localized corrosion;
— Thermal creep;
— SCC;
— Delayed hydrogen cracking (DHC);
— Embrittlement (hydride reorientation, hydrogen migration and redistribution);
— Oxidation (fault conditions).

The importance of an individual degradation mechanism is dependent on whether the spent fuel is in wet or dry storage, as a number of the degradation mechanisms only have the potential to impact fuel in dry storage systems. Each of these mechanisms and underpinning research is described in greater detail in the final reports of the IAEA Coordinated Research Projects (CRPs) Behaviour of Spent Power Reactor Fuel During Storage (BEFAST-I, II and III) [31–33] and Spent Fuel Performance Assessment and Research (SPAR-I, II and III) [12, 34, 35]; a summary of the work completed can also be found in Ref. [9]. The scope of these CRPs included all thermal power reactor fuel: zirconium clad fuels used in boiling water reactors (BWRs), CANDU, heavy water reactors (known as HWR), PWR, high power channel type reactor (RBMK) and water-water energetic reactors (WWER); stainless steel clad fuels used in gas reactors; and in the earlier studies, historical thermal reactor fuels that are no longer manufactured, such as stainless steel clad LWR and MAGNOX fuel. Table 1 and the following sections provide a high level summary of the findings.

TABLE 1: SUMMARY OF POTENTIAL SPENT FUEL DEGRADATION MECHANISMS IN WET AND DRY STORAGE AND THEIR POTENTIAL FOR LOSS OF FUEL CLADDING INTEGRITY

Degradation mechanism	Storage			Transport after storage
	Wet/dry	Normal operation conditions	Anticipated operational occurrences	
Uniform corrosion	Wet	No	Yes	No
Localized corrosion	Wet	No	Yes	No
Thermal creep	Dry	No	Yes	No
Stress corrosion cracking	Wet/dry	No (except AGR)	Yes	No
Delayed hydride cracking	Dry	No (except CANDU)	No	No
Cladding embrittlement	Wet/dry	No	No	Yes
Oxidation	Wet/dry	No	Yes	No

5.1.2.1. Wet storage

The transition of the spent fuel from >300°C in the reactor core to pool temperatures of <50°C results in a significant decrease in stressors such as residual internal pressure, hoop stress and rates of corrosion.

Degradation mechanisms that may affect zirconium based fuel cladding integrity during wet storage are illustrated in Fig. 48, and those that can affect stainless steel clad fuel from gas reactors are in Fig. 49.

The main degradation mechanisms that have the theoretical potential to affect spent fuel cladding and structural component integrity during wet storage are uniform corrosion, localized corrosion, SCC, cladding embrittlement and oxidation. The following summarizes those mechanisms.

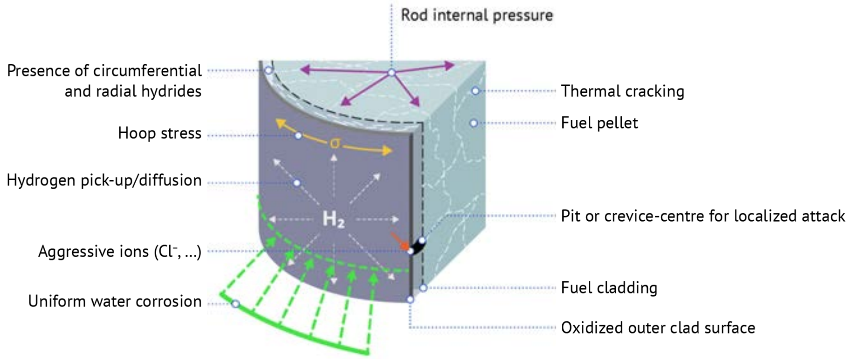

FIG. 48. Schematic illustration of phenomena that may affect spent zirconium fuel cladding performance during wet storage.

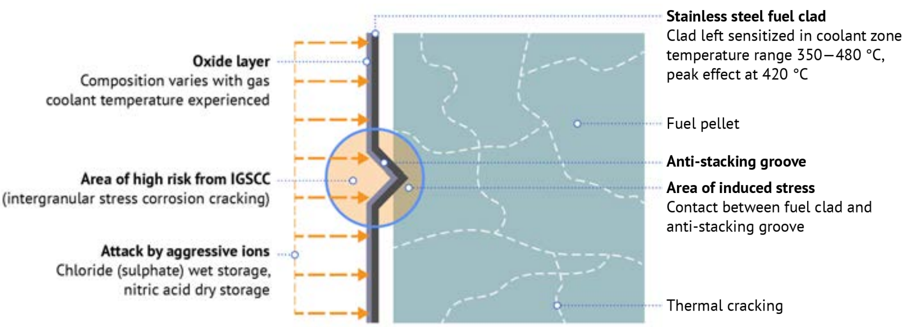

FIG. 49. Schematic illustration of phenomena that may affect spent stainless steel gas reactor fuel cladding performance during wet storage and dry storage.

(a) Uniform corrosion

When stored in good quality pool water, uniform corrosion rates of zirconium based alloys at temperatures <50°C are below the limit of detection of standard measurement tools. Uniform corrosion is therefore not considered a limiting factor for the prolonged storage of fuels with zirconium based cladding, provided the pool chemistry is controlled as specified by the fuel manufacturer.

Reported data for zirconium and stainless steel based cladding materials and materials used in fuel assembly structures or bundles — stainless steel (304L) and Inconel (625, 718 and X-750) — are provided in Table 2.

TABLE 2. UNIFORM CORROSION DATA FOR FUEL ASSEMBLY CLADDING AND STRUCTURAL MATERIALS STORED IN WATER

Material	Uniform rate of corrosion	Remark	Ref.
Zry-1	3–5 µm/yr	RBMK in stagnant water cans, otherwise corrosion is below the limit of detection.	[16]
Zry-2	<0.01 µm/yr	Extrapolated data from 90°C. Measured data shows an initial growth of ~3.7 µm oxide in 2 years in wet storage followed by no further measurable growth.	[38] [16]
Zircaloy specimens	<0.007 µm/yr	Immersion in pool water for 3 years.	[37]
Stainless steel cladding (20Cr:25Ni:Nb)	<0.1 µm/yr	Unirradiated cladding in pH11.5 demineralized water + sodium hydroxide, immersion and field signature method tests.	[34]
Inconel alloys (625, 718 and X-750)	0.05 µm/yr	Concentrated well water ~72 ppm chloride.	[39]
Zry-4	50 nm/yr (limit of detection)	Irradiated Zry-4 in demineralized water, demineralized water + sodium hydroxide to pH11.4, demineralized water + sodium nitrate 50 ppm. All tests at 323 K.	[35]
Stainless steel (304L)	0.25 µm/yr	Coupons in pool water.	[37]

(b) Localized corrosion (galvanic, pitting and MIC)

In wet storage, where the pool water acts as an electrolyte, galvanic corrosion is the preferential attack of one of two electrically dissimilar metals that are in electrical contact. Galvanic corrosion is an area of potential concern for fuel assembly materials in contact with storage racks, containers, etc.

Stainless steel finds common use in storage racks and containers because, like zirconium alloys, it is at the near noble end of the galvanic series and therefore no electrochemical attack occurs. The evidence to date supports that this is the case. The other material that has found use in storage is aluminium.

Aluminium alloys — near the active end of the series — if in electrochemical contact with zirconium alloys, could theoretically generate enough potential to oxidize the aluminium and hydride the zirconium. In reality this does not happen because both materials readily form passivating oxide layers that act as a barrier, preventing the materials from coming into direct electrical contact with one another [34].

Zirconium based alloys and stainless steel based materials are not susceptible to pitting corrosion under normal water chemistry conditions that exist in spent fuel pools, that is, where impurities are kept below 2 ppm. MIC is the result of metabolic activity by some bacteria species, particularly by sulphate reducing bacteria in stagnant water. While there has been some evidence for MIC in cooling structures, the MIC of zirconium based alloys and pool storage equipment has not been observed. Periodic sampling to detect harmful species can be implemented as a precautionary measure, especially for outdoor storage facilities.

(c) Stress corrosion cracking (stainless steel clad fuels only)

If stainless steel clad gas reactor fuel has been irradiated in the temperature range of 350–480°C, it is left sensitized at the beginning of storage (Fig. 49). In combination with areas of residual stress (end caps or antistacking grooves), this fuel cladding is susceptible to failure through intergranular SCC if aggressive ions are present (e.g. chloride). Experience has shown that very low concentrations of chloride <0.5 ppm can initiate corrosion [35].

(d) Cladding embrittlement — Hydrogen migration and redistribution in fuel assemblies containing zirconium

When zirconium cladding fuel is cooled to the pool storage temperature, most hydrogen in solid solution in the alloy precipitates in the form of hydride platelets. At the pool water temperatures of practical interest, it is possible to rule out hydrogen redistribution by thermal diffusion and formation of so-called ‘pits’ by an Ostwald ripening due to water’s heat transfer characteristics.

(e) Oxidation in failed fuel

The primary source of oxygen in pool water is dissolved oxygen. As most storage systems used in spent fuel storage are open or ventilated, the potential for oxygen buildup from radiolysis can be discounted. Dissolved oxygen levels in pool water are highest at low pool temperature levels: 10 ppm at 15°C reducing to 7–8 ppm at 45°C. At these levels they do not pose a particular problem to intact fuel cladding and structural materials in pool water. If fuel is exposed due to failed cladding, there is potential for the exposed fuel to convert to higher oxides. Conversion at a reasonable rate requires elevated temperature, which does not exist in pool environments. Any conversion is therefore relatively slow in comparison.

In the case of failed fuel, research and operating experience has shown the results to depend on the defect size. For defects <1 mm, there is little evidence to support conversion to higher oxides. For large defects, it has been reported that the cladding may rupture due to the formation of higher oxides. For fuel stored a long time, conversion towards the higher oxides is evidenced by the formation of yellow crystals or powder on the surface of the dioxide pellets.

5.1.2.2. Dry storage

Fuel may be transferred into dry storage after initial cooling in the reactor pool. The processes of drying fuel followed by dry transfer and storage could expose the fuel to higher temperatures than in the pool and potentially higher than those experienced during irradiation. The fuel is also exposed to relatively rapid pressure changes if vacuum drying is used.

Transitioning from pool storage temperatures of less than 50°C to up to 400°C [20] during drying and 350–410°C in dry storage, depending on national regulations, will result in an increase in stressors such as internal pressure and hoop stress. The post-irradiation conditions existing in an LWR fuel pin section that can impact fuel cladding (zirconium based) integrity in dry storage are shown in Fig. 47 (right); those for stainless steel clad gas cooled reactor fuels are shown Fig. 49.

Potential degradation mechanisms that may affect fuel cladding integrity during dry storage and subsequent handling and transport operations are thermal creep, SCC, delayed hydride cracking (DHC), cladding embrittlement and air oxidation. These are summarized below.

(a) Thermal creep

Fuel cladding creep is a process in which the length or diameter of the material increases with time as a result of one or more applied stressors. As the material expands, it will become thinner until it ruptures, which is postulated to lead to a ‘pinhole’ (or tight crack) type of rupture. The creep process is characterized by three phases: an initial rapid increase in length or diameter which slows in time, a period of uniform increase, then an exponential increase until the material ruptures. The phases are commonly referred to as primary, secondary and tertiary creep (Fig. 50). From a nuclear safety perspective, the

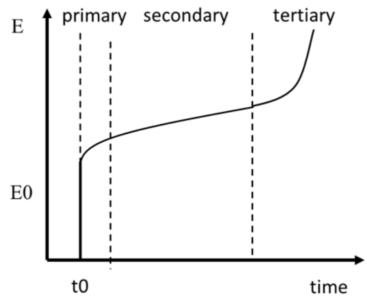

FIG. 50. Thermal creep characteristics.

main aim is to avoid the conditions that would lead to tertiary creep. For fuel cladding, the stressors are internal fuel rod pressure and cladding temperature. Creep is also a function of material composition and condition and annealing effects during storage [40].

During extended storage, the volume of gas inside a fuel rod after initial cooling at reactor is estimated to remain constant[18] and, therefore, the main factor which will impact a transition in creep rate will be the fuel cladding temperature.

For water reactor fuel, if the spent fuel is subsequently transported or transferred into a dry storage system, there is potential for the fuel cladding temperature to increase above the values seen during reactor operation. Thermal creep therefore was considered to be one of the most limiting degradation mechanisms in dry storage but has since been shown to be a self-limiting mechanism. Further information is found in Refs [9, 40].

(b) Stress corrosion cracking

SCC of fuel cladding in dry storage can occur either by internal attack through iodine induced SCC, or by external attack as in the case of stainless steel clad gas reactor fuel by intergranular SCC (see Fig. 49 and Section 5.1.2.1.c). Intergranular SCC in dry storage occurs as a result of nitric acid attack from radiolysis in stagnant or low flow air conditions, and in sealed systems filled with inert gas with trace amounts of air and residual moisture [41].

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[18] After initial cooling, further gas release from the fuel matrix would not be expected, but over the longer term (>100 years) helium accumulation from alpha decay could result in additional gas being released from the fuel matrix and/or pellet fracture, resulting in additional stress on the fuel cladding [35].

In the case of iodine induced SCC (where iodine is the aggressor), it will occur only in the presence of chemically active iodine, adequate stress and a specific high temperature range. At temperatures typical of dry storage regimes, the fission products that are generated in UOX fuel during reactor operation are practically immobile in the fuel lattice, and iodine is not present in a form that could trigger SCC.

It can be concluded that as the combination of SCC agent and stress conditions required for crack propagation are normally absent, cladding failure via this mechanism is not expected to occur. As a result, SCC, uniform fuel rod internal fission product corrosion of the cladding, localized fuel rod internal fission product corrosion of the cladding and other fission product driven defect mechanisms are also not expected. Further information on this is found in Ref. [15].

(c) Delayed hydride cracking

DHC is one of the many ways in which hydrogen induced cracking of zirconium based alloys can occur. DHC is a very specific mechanistic process that requires triaxial stressing of the zirconium to dilate the crystal lattice. Zirconium lattice tetrahedral sites occupied by hydrogen atoms in solution are dilated by these triaxial stresses. As a result, hydrogen atoms can diffuse up the stress gradient and precipitate in the peak stress region. Despite observations of the DHC mechanism in thicker Zircaloy specimens, it is not expected to be an active degradation mechanism in cladding tubes because wall thickness is insufficient to generate much triaxial stress.

For a specific population of CANDU fuel bundles, the most critical mechanism that could affect their integrity during dry storage is considered to be DHC of the endcap and endplate welds; this population is known to have endplate weld regions with discontinuities. The basis of this concern relates to the potential for enhanced stresses to develop in the weld region from fuel bundle to endplate as a result of bending. Finite element modelling supported by experimental studies suggest the calculated stress intensity factor in the endplate is around half the critical stress intensity factor to cause crack propagation [42].

(d) Cladding embrittlement

Cladding embrittlement, or a loss of cladding ductility, increases during exposure to fast and thermal neutrons at elevated temperatures as a result of radiation induced damage. For fuels irradiated <500°C, ductility loss is primarily caused by fast neutron damage in the form of point defect clusters (dislocation loops and voids). These clusters act as dislocation, restricting their ability to glide under stress.

In the case of stainless steel clad gas reactor fuels in which most of the fuel stringer is irradiated at >500°C, point defect clusters anneal too rapidly to have a significant impact on cladding ductility. Stainless steel was also chosen on the basis that it retains a high degree of ductility at high temperatures. However, stainless steel does lose ductility during irradiation as a result of helium formation. There are three sources of helium:

— Transmutation of boron;
— Transmutation of nickel;
— Fast neutron reaction with metal atoms.

At high irradiations, the (n,α) transmutation of nickel (^{58}Ni or ^{60}Ni) to iron (^{55}Fe or ^{57}Fe) dominates.

In the case of zirconium clad fuels in water reactors, the cladding also loses ductility as a result of hydrogen pick-up from the water coolant and subsequent reaction with zirconium in the cladding structure. This reaction forms zirconium hydride platelets that precipitate out of solution when the fuel cladding is cooled down. There are two embrittlement related degradation mechanisms, which have the potential to affect fuel integrity during storage and subsequent handling and transport operations: (i) hydride reorientation and (ii) hydrogen migration and redistribution.

(i) Hydride reorientation

Hydride reorientation is a process whereby precipitated zirconium hydrides dissolve into the solid metal matrix up to the point of hydrogen saturation and can reorient into a different direction during cooling under inner pressure of the rod. If the hydride reorients from the circumferential to radial direction, the mechanical properties of the fuel cladding can be impacted. While this does not affect spent fuel performance in storage, it has the potential to influence subsequent spent fuel handling operations; particularly at lower temperatures if the fuel is dropped or impacted during transport. The susceptibility to hydride reorientation increases with temperature and stress; short cooled, higher burnup and MOX fuels are the most susceptible.

There has been a considerable amount of research into the properties that influence zirconium hydrides to reorient during fuel drying, storage or transport operations. Studies have included:

— The effect of temperature on hydride reorientation;
— The effect of stress on hydride reorientation;
— The effect of radial heat treatment conditions on cladding ductility;

— The effect of power reactor irradiation on ductility;
— The effect of cooling rate;
— The ductile-to-brittle transition temperature (sometimes known as DBTT).

The studies are reported in detail in Ref. [35]. The main findings are summarized here:

The maximum cladding temperature after or upon cooling determines how much hydrogen goes back into solid solution in the zirconium based alloy matrix. Typically precipitated hydrides will dissolve at a different temperature from the one that they re-precipitate at (i.e. show a hysteresis), and it is during this re-precipitation where the cladding stress is most relevant for assessing the potential for hydride reorientation. Reorientation will increase with a higher applied stress; interaction between the pellet and cladding will likely result in a significantly reduced stress compared to instances where there is no bonding.

The susceptibility of cladding with applied tensile hoop stress to the precipitation of radial hydrides during cooling has been shown to be significantly impacted by texture. The effect on material properties (including grain size, internal stress/strain etc.) caused by heat treatment needs to be accounted for in interpretation of the results.

There is some evidence to support that rapid cooling leads to shorter hydrides (particularly for PWR fuels). In the case of BWR fuels containing a zirconium liner, however, the liner acts as a hydrogen sink, so a longer cooling period lowers the amount of hydrogen available for reorientation as the liner absorbs it preferentially.

(ii) Hydrogen migration and redistribution

The existence of axial temperature profiles in the storage system can cause the migration of hydrogen in solid solution from the high temperature to the low temperature region of the cladding [43–45]. The precipitation of hydrogen will occur in the colder regions in the form of hydrides if, and only if, a high enough supersaturation is realized. When this is the case, precipitation of hydrides leads to increased embrittlement, which may affect fuel integrity.

Because the hydrogen diffusion coefficient has a low value, following 40 years of storage under a helium atmosphere, any axial hydrogen migration is insignificant, with the exception of fuel rod ends. As changes between the initial and post-storage hydrogen profile were insignificant, it was therefore concluded that hydrogen migration has no significant effects on fuel cladding integrity during dry storage.

(e) Air oxidation

The presence of significant amounts of air in contact with stored spent fuel can be ruled out by appropriate drying and inerting of systems to ensure inert atmosphere conditions during dry storage. When stored in normal conditions, oxidation beyond that incurred during reactor duty is not to be expected. Therefore under normal inert storage conditions, oxidation is not an active degradation mechanism. In the case of off-normal or accident conditions where there has been a failure of the storage system's seals, air oxidation could be considered a degradation mechanism.

For such an off-normal or accident condition, two scenarios can be considered for the fuel rods: (i) no through-wall defects present, resulting in cladding oxidation; and (ii) through-wall defects present, resulting in fuel matrix oxidation.

(i) Air oxidation of cladding

At typical dry storage temperatures and conditions,[19] the oxidation rates of zirconium based cladding by air are relatively low [46]. As a result, this limits cladding wall thickness losses to a few per cent, even if there is prolonged air exposure. Due to this limitation, the cladding remains an effective containment barrier and, if there are no through-wall defects present in the cladding, the fuel pellets remain protected from air exposure.

(ii) Air oxidation of fuel matrix

When through-wall defects are present in the cladding, such conditions can result in air coming into contact with the fuel pellet. When temperatures are below ~250°C, the oxidation rates of UOX remain very low. However, if the temperature is greater than 250°C, the formation of U_3O_8 from UO_2 becomes possible via the two step process of $UO_2 \rightarrow U_4O_9 \rightarrow U_3O_8$.

This conversion to U_3O_8 is temperature and fuel burnup dependent (see Ref. [47] for further information). The transition results in a volume expansion of greater than 36%. The increase in volume as fuel oxidizes to U_3O_8 results in high stress levels on the cladding; gross cladding rupture or 'unzipping' may result.

[19] Using the equation developed by Hillner et al. [46], it is predicted that, for fuel held at 400°C for 100 days, only 20 μm of additional cladding would be lost. While this equation was developed for steam corrosion, the corrosion rates in steam and air are similar enough to give a representative result.

5.2. SURVEILLANCE

As shown in Fig. 46, surveillance is one of the major processes in the plan-do-check-act cycle of ageing management of spent fuel and storage facilities. Safety functions of both the spent fuel and storage facilities have to be evaluated in consideration of potential ageing degradation of the components [48, 49]. For spent fuel storage facilities, safety related SSCs therefore require monitoring and inspection. Resources need to be focused on the high priority ageing concerns.

Monitoring is defined as “continuous or periodic measurement” [4]. Inspection is defined as “an examination, observation, measurement, or test undertaken to assess structures, systems and components” [4]. In storage facilities, ongoing verification is required to ensure that critical SSC performance remains adequate to meet its requirements. Effective ageing management would ensure that any reduction in performance is detected early and in advance of any loss of safety function.

Monitoring may be performed by either condition monitoring or performance monitoring. Condition monitoring is used to identify the presence of ageing effects or any damage and to quantify their extent. This includes the inspection of spent fuel, fuel storage racks and concrete structures for any degradation. Performance monitoring is used to verify whether the SSCs have the ability to perform their intended functions.

The inspection programme ensures that the SSCs fulfil all applicable storage requirements (and transport requirements in the case of DPCs), and includes:

- Periodic inspection of the storage system with results recorded in a report;
- The potential for random inspections of the storage system;
- Evaluation of the results of recurrent inspections.

As there are evolutions in regulations and technology, periodic reassessments of the condition of the storage system ensure that the storage licensing basis remains in compliance throughout the storage period. The transportation regulations applying to DPCs are described in IAEA SSR-6 [50], as outlined in Section 6.2.1.[20]

Evaluation of the ongoing condition of SSCs requires information from several sources such as the operating history, inclusive of corrective actions and design modifications. Experience gained at the specific site, in addition to relevant

[20] Paragraphs 809 (f) and (k) of the Regulations for the Safe Transport of Radioactive Material, IAEA SSR-6 (Rev. 1, 2018) [50] require consideration of ageing mechanisms and a programme for a periodic evaluation of changes of regulations, changes in technical knowledge and changes of the state of the DPC design during storage.

industry-wide experience, can also be considered part of the overall condition assessment of SSCs. As a best practice for industry-wide or countrywide systems, the trends in monitoring, inspection results and corrective actions ought to be collected and analysed.

5.2.1. Wet storage

Generally, spent fuel and fuel storage racks can be easily observed in wet storage through the water. Some SSCs are accessible to direct inspection during service. There are other SSCs that are inaccessible or are located in high radiation fields and so are not readily accessible for close examination. Methods to assess the status of a material's condition in wet storage facility may include [37]:

— Non-destructive evaluation;
— Destructive examination of actual and/or representative materials;
— Underwater photography and video cameras;
— Inspection of any components removed from service, whether that be during maintenance or decommissioning;
— Water chemistry and radionuclide monitoring.

Spent fuel surveillance programmes can be implemented. For example, in French AR pools, ten spent fuel assemblies are in a monitoring programme: six UO_2 (with different enrichment and burnup) and four MOX spent fuel assemblies. The last examinations were performed after a storage period of 25 years. Results showed that there was no loss of leak tightness, no geometrical deformation and no change of the oxide layer thickness. In the planned centralized wet storage facility, this surveillance programme will be continued with an increased number and variety of spent fuel assemblies concerned. Extraction of a rod from a spent fuel assembly may be possible in order to perform destructive examination in a dedicated laboratory.

5.2.2. Dry storage

In dry storage, direct visual spent fuel inspection is not possible without opening the storage system or unit, which could potentially introduce moisture or air into the system or unit and could present a risk to fuel integrity. It would also increase radiation exposure for workers, so methods that maintain radiation exposure ALARA would be preferable. In most systems, it is also not possible to sample the storage cavity gas for analysis. Alternative methods used to assess the status of dry storage systems include:

— Dose rate measurement;
— Leak detection, for example by inner-lid pressure measurement;
— Temperature measurements, in flow passages or storage system external surface.

In addition, periodic inspections can be performed, which are mandatory in some countries. For example, more detailed inspections of a certain percentage of canisters, storage units or casks (minimum of one) already in storage can be undertaken, such as a visual check for degradation, dose rate or temperature measurements. Those inspections may be part of a safety justification for storage licence renewal.

Tokyo Electric Power Company (TEPCO) conducted investigations in 2000 and 2010 of casks stored for five and ten years. A further investigation was undertaken on casks stored for 17 years at Fukushima Daiichi NPP in 2013, following the 2011 Fukushima Daiichi accident. During the 2011 tsunami, sea water, sand and debris had hit the cask storage facility and was deposited in the building. After confirmation of the safety performance by visual inspection, the nine storage casks were transferred to the on-site common pool. Further inspections were undertaken to confirm containment, subcriticality and fuel integrity. The first of the nine casks was immersed in the pool, and the primary lid was removed to investigate the contents. The investigation confirmed that there were no abnormalities on the cask bodies or any abnormalities in the external appearance of the three representative spent fuel assemblies that were taken for inspection. Removal of the primary lid of the other eight casks would only be considered if the primary lid seal were found to be leaking or if 85 Kr were detected. No issues were found, so investigations of the remaining eight casks were performed in the air atmosphere of the common pool building. In all cases, the secondary lid seal was replaced due to seawater corrosion.

Japan Atomic Power Company (JAPC) conducted the investigations on the leak seal tightness and soundness of the spent fuel cladding of seven year stored casks in 2009. To confirm the leak tightness of the casks, an external appearance inspection was conducted on both the primary lid metal seal and the flange seal to confirm that gas was not leaking. To confirm the soundness of the spent fuel cladding, gas samples from the cavity were taken and analysed, and a visual inspection of a spent fuel assembly was carried out. A similar examination of an opened cask following 15 years of storage was undertaken in the USA [51, 52].

Through these investigations, TEPCO and JAPC have proven the leak tightness of the casks and soundness of the spent fuel cladding after 17 years of storage. These types of investigation are essential to demonstrating continued safety performance and to supporting transportation after storage.

Some additional examples of surveillance for specific features of casks are described in Ref. [53].

5.2.2.1. Shielding

Deviations from expected radiation levels could indicate shielding degradation. For example, polymeric neutron shield materials in dry storage casks are subject to thermal and radiation induced degradation.

5.2.2.2. Confinement

For metal cask storage, inert gas leakage can be checked through pressure monitoring between cask lids. An example of a pressure monitoring system is shown in Fig. 51. For some welded canister systems, inert gas leakage can potentially be checked through the measurement of the temperature difference between the top and bottom of the canister [54].

For the licence renewal of canister based concrete cask storage systems, demonstration that canisters have not undergone any unanticipated degradation is a necessary stage to ensure that the canister retains its confinement function. Remote visual inspection of one or more 'lead canisters' is an accepted approach in the USA, according to the Nuclear Regulatory Commission, to verify canister

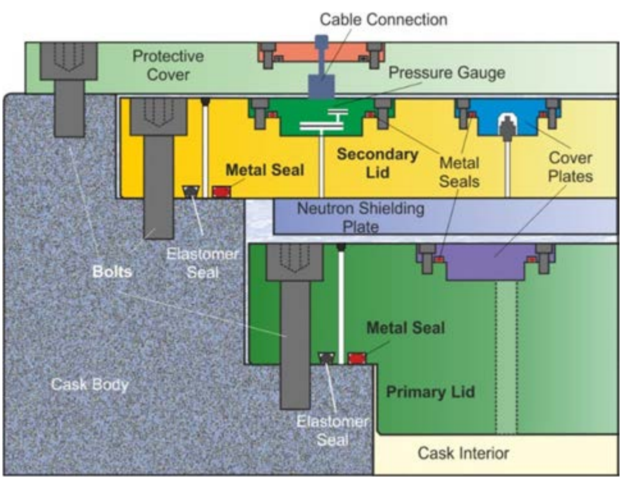

FIG. 51. Typical double barrier bolted closure system of CASTOR cask types (reproduced courtesy of Bundesanstalt für Materialforschung und -prüfung (BAM)).

conditions at an independent spent fuel storage facility [55]. A lead canister is selected by the applicant justifying the selection of the canister to be examined.

5.2.2.3. Cooling

For a storage system with internal air flow passages (e.g. concrete casks), appropriate inspection intervals and/or air temperature monitoring systems could be considered and included in the operating procedures or system design.

The air temperature monitoring system, designed to provide verification of heat dissipation capabilities (i.e. to measure the outlet air temperature of the concrete casks in long term storage), can be designed for remote or local readout capabilities. The temperature monitoring system can be installed on all or some of the concrete casks.

For canister based systems, monitoring of the canister surface temperature distribution is one possible method used to detect a leak. If canisters have been filled with helium to improve heat conductivity, the temperature distribution will change if a crack forms and inert gas subsequently escapes [9, 35].

5.3. MAINTENANCE AND REPAIR

To ensure the performance and proper condition of the dry storage system after long term storage and prior to shipment, it is necessary to implement maintenance and repair programmes or procedures as part of the operations based AMPs.

In a wet storage facility, most of the safety functions are at least partially performed by active systems (cooling, pool water purification, building ventilation). During operation of such storage facilities, routine maintenance and non-routine maintenance in response to monitoring and inspections, periodic visits and inspections are necessary. These activities ought to be integrated into the design.

Dry storage systems are typically designed as passive units requiring minimal maintenance. For this reason, there are no active components or systems required to assure the continued performance of its safety functions during storage operations. However, non-routine maintenance would be required when abnormal signals are observed in the monitoring of the performance, such as confinement or cooling. Routine maintenance procedures ought to be developed for the service life of the equipment and provided to the operator to cover maintenance operations such as the lubrication of moving parts and the reapplication of corrosion inhibiting materials if scratches occur. Some materials and plant items have a finite life and will need to be replaced. Items requiring periodic replacement are normally identified during design, and a refurbishment programme is incorporated into the plant maintenance system. Other considerations that may be outside of the operator's control also need to be routinely monitored, but adequate provision can be made if they are known. Such considerations include the availability of spare parts and a diversity in the marketplace. One important area is control systems and computer systems that might become obsolete and are no longer supported.

5.4. DATA PRESERVATION

Documents about nuclear fuel containing data, information and knowledge are diverse in nature (paper document, spreadsheets, email, web site content, etc.), complex and voluminous. In planning for any activity at the back end of the fuel cycle, it is necessary to have as complete knowledge as possible.

The purpose of records is to keep and maintain information and up-to-date drawings so that this information can be used when detailed planning for further activities begins.

In preparation for any future activities, one of the first tasks is identifying what information is required, determining the proper sources of this information and establishing effective controls over it.

An important element of planning is the identification and storage of appropriate design and operational records prior to the final shutdown of a nuclear facility to prevent the loss of operating experience.

The most important decision in record keeping is to address the following:

— What type of information is to be stored;
— In what form it is to be kept;
— The quality of the information in both type and form;
— The ease of future retrieval of information, even after very long periods of time.

In some Member States, a records management system — or document management system — needs to be established and implemented by the responsible organization as the records are developed or obtained and released for use. This enables an organization to create, index, search, save and locate documents containing design information that is stored electronically. More information on data preservation can be found in Ref. [56].

6. SPENT FUEL TRANSPORTATION: CONSIDERATIONS ASSOCIATED WITH SPENT FUEL STORAGE

At some point in time, spent fuel will need to be transported from the reactor site for either further storage, reprocessing or conditioning for disposal. On-site transfers of spent fuel are governed by local site requirements and will not be covered in this chapter.

A spent fuel transport cask consists of a main body, basket (in the case of a bare fuel cask) or canister and a closure system. These components assure the safety functions related to transport such as containment, criticality, thermal release and radiological shielding which are supported by structural integrity during routine, normal and accident conditions (IAEA SSR-6) [50].

Trunnions at the bottom and top of the casks are generally included in the design for lifting or rotating operations. They are also used as part of the tie down system on cradle or transport platforms. Transport casks for spent fuel are categorized as a Type B (U or M) package in accordance with IAEA and most country specific regulations, with the requirements for packages containing fissile material also taken into account. An example is shown in Fig. 52.

A transport package design approval certificate is normally issued for a fixed period (a typical duration is five years), and its renewal for the next period will require demonstration of compliance with the transport safety requirements of the transport regulations at the time of the recertification process. In contrast, a storage licence is usually issued for decades.

FIG. 52. NAC-STC transport cask being transported by truck on road (courtesy of NAC).

6.1. TRANSPORT FOR STORAGE ONLY SYSTEMS

Off-site transportation (over public roads) of spent fuel uses a transport cask, forming a complete transport package that is approved by the competent authority. For facilities using a storage only system, it is important to maintain the ability to transfer the fuel into a transport cask to move it to the next step of the management process (either to another storage facility, a reprocessing plant or a disposal facility). This could be a hot cell or a wet or dry transfer facility for reloading bare fuel or canisters.

In the case of a horizontal storage system, a sealed metal canister is pulled out of the horizontal storage system and placed into a metal transfer cask. The cask is then transferred to the reactor building or transfer station for moving the fuel into a transport cask or a DPC. For silos (vertical storage system), a temporary crane may need to be brought to the storage facility to perform the vertical lifting for transferring the canister to a metal transfer cask. The cask is then tilted horizontally and transferred to the reactor building or transfer station to move the fuel into a transport cask or a DPC.

If the reactor building has been decommissioned, a stand-alone transfer station (hot cell, intermodal facility) ought to be maintained at the storage site to move the fuel into a transport cask or a DPC.

6.2. TRANSPORT FOR DUAL PURPOSE SYSTEMS

6.2.1. General considerations

The rationale to use DPCs is that they provide a means to store spent fuel safely in a cask and that, with the spent fuel, they constitute a package that can also be transported [57].

This strategic approach involves issues that need to be addressed such as demonstrating compliance with the transport safety regulations at the time of shipment. As stated before, package design approval and storage licences cover different durations, and maintenance of both is important to ensure future transportability. Obtaining a package design approval for an old and already loaded cask at a later time may be very difficult due to the need for inspections in areas that are difficult or impossible to access.

IAEA SSR-6 (Rev. 1) [50] introduced the following to be considered for ‘shipment after storage’ for DPCs:

> 503(e): “For packages intended to be used for shipment after storage, it shall be ensured that all packaging components and radioactive contents have

been maintained during storage in a manner such that all the requirements specified in the relevant provisions of these Regulations and in the applicable certificates of approval have been fulfilled."

809(f): "If the package is to be used for shipment after storage, a justification of considerations to ageing mechanisms [shall be included] in the safety analysis and within the proposed operating and maintenance instructions."

809(k): "For packages which are to be used for shipment after storage, a gap analysis programme [shall be included] describing a systematic procedure for a periodic evaluation of changes of regulations, changes in technical knowledge and changes of the state of the package design during storage."

In most cases, the limiting factor for loading a DPC is the heat load of the system and not the number of fuel assemblies. This means that fuel assembly capacity alone is not indicative of the most economic DPC solution for a given inventory; one has to find the right combination of tolerable heat load and fuel assembly capacity. As illustrated in Table 3, casks are often available in different configurations depending on the specific fuel to be loaded. By using different storage baskets available for the many of the designs, the capacity can be adjusted to reflect the actual requirements. Figure 53 shows an example of a DPC with configurations in transport stage (a) and storage stage (b).

TABLE 3. EXAMPLES OF DPC CAPACITIES FOR DIFFERENT FUEL TYPES

Cask	Fuel type	Number of fuel assemblies	Tolerable heat load (kW)
CASTOR V/52	BWR	52	40
ENUN 52B	BWR	52	13[a]
HI-STAR 80	BWR	32	54
HTZ 52B	BWR	52	12.8[a]
TN 24BH	BWR	69	35
HI-STAR 63	CANDU	120	0.75
OPG DSC[b]	CANDU	384	2.5
CASTOR GEO	PWR	32	40
ENUN 32P	PWR	32	36

TABLE 3. EXAMPLES OF DPC CAPACITIES FOR DIFFERENT FUEL TYPES (cont.)

Cask	Fuel type	Number of fuel assemblies	Tolerable heat load (kW)
HI-STAR 180	PWR	37	32
TN 24G	PWR	37	30
TUK-109	RBMK	144[c]	7.8/5[c]
TUK-137T.A1	WWER	18	21.6
TUK-137T.E	WWER	18	30
TUK-151	WWER	18	36
CASTOR 440/84	WWER	84	22.6[a]

[a] Designed for low heat load as per customer request.
[b] Dry storage container.
[c] Standard/non-standard fuel bundles.

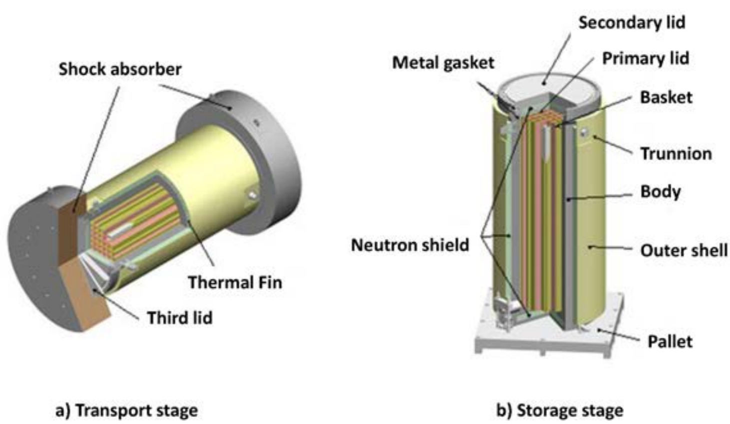

FIG. 53. Example of a DPC with configurations in (a) transport stage (~130 t) and (b) storage stage (~120 t). The length of the DPC (Hitachi GE) is approximately 5.4 m and the outer diameter is approximately 2.5 m. Sixty-nine BWR fuel assemblies can be loaded.

6.2.2. Operational aspects for post-storage transportation

One of the main functions of DPCs is to ensure transportability after storage. Examples of inspections before shipment, a timeline for the licensing procedure and so forth are specifically described in the following subsections.

6.2.2.1. Pre-shipment inspection after storage period

Transport after storage requires a combination of inspection and evaluation of the DPC package which often includes, but is not limited to:

- External appearance (check for corrosion, degradation of sealing material);
- Leak tightness in relation to the transport regulatory requirements (to be measured);
- Dose rates in relation to transport regulatory limits (to be measured);
- Subcriticality (check documentation and AMP reports);
- External surface temperature (to be measured);
- Lifting capability (check of trunnions and attachment points);
- Condition of contents (check documentation and AMP reports);
- Surface contamination in relation to transport regulatory limits (to be measured);
- Storage environment records to demonstrate compliance with the storage conditions (check of documentation).

Transport package approval of DPCs is normally renewed every five years during storage. Because inspections are difficult to perform after loading, the package design safety report (PDSR) justifies the acceptable performance of the package without the need to open the cask.[21] A DPC that is approved by the competent authority needs to have a valid transport package design approval certificate to enable the DPC to be transported in the public domain after the storage period. The time allocated to complete any required analysis and approval process has to include the time to remove the DPCs from the storage facility if the application for an extension to the authorized storage period fails.

It is important to develop a process that provides an ongoing mechanism to ensure that all aspects are considered, namely:

- The number of DPCs in storage;

[21] This approach also maintains radiation exposure to workers ALARA, in comparison to opening the DPC for inspection.

— The lead time to procure shock absorbers and transportation assets such as lifting equipment, transport frames, road trailers, rail wagons and inspection equipment, taking into consideration some of these items may be bespoke;
— Required training for staff;
— The time needed to remove all the DPCs to another location;
— Restrictions on throughput from the transport infrastructure, routing or the receipt facility;
— Necessary stakeholder consultations.

6.2.2.2. Example of a concept for alternative inspections

In Japan, advisory working groups to the government proposed alternative inspections to prove transportability after storage without the need to open the cask lid, which can be incorporated into the transport package approval of the DPCs [58]. In combination with the ageing management evaluation, these are intended to give assurance that the DPC package can be safely transported without inspections of the inside of the cask, which are impossible to perform on a loaded cask without a specific hot cell. All this would be part of the PDSR submitted for package design approval certification for transport and storage.

The following subcriticality inspection is an alternative to an intrusive inspection method during pre-shipment inspections, subject to acceptance and approval by the competent authority and accounting for ageing and degradation mechanisms, as mentioned in Section 5.

There is reasonable assurance that no significant deterioration of the criticality safety function has occurred if the following can confirmed:

— Basket manufacture has been undertaken in compliance with the PDSR specified design;
— On completion of loading, moisture was removed and inert gas was filled in accordance with the PDSR requirements;
— DPC packages comply with the PDSR referenced in the package design approval certificate;
— Maintenance of the inert atmosphere neutron absorbing material during storage was achieved;
— The storage facility and the corresponding DPC storage environment and conditions were maintained throughout the storage period inside the limits specified in the safety report.

In some cases, the competent authority may approve documents demonstrating the above points.

7. SECURITY AND SAFEGUARDS ASPECTS

Extensive guidance on the security and safeguards aspects of spent fuel storage are available from the IAEA. A brief summary of salient information is given in the following section. Please see the reference materials within the text for more in-depth details.

7.1. SECURITY AND PHYSICAL PROTECTION

SNF, due to its radioactive nature and criticality issues, is considered a target for possible attack scenarios, which include both unauthorized removal as well as sabotage attacks. Such attack scenarios can be carried out by various threats with different motivations, intentions and capabilities resulting in a range of potential consequences depending on the characteristics of the facility as well as any post-attack mitigative actions.

Scenarios involving unauthorized removal of SNF are primarily associated with use in the development of a nuclear explosive device or a radiological dispersal device. Scenarios involving sabotage of spent fuel in wet storage are associated with the loss of the cooling and shielding water in the pool. Spent fuel pools containing recently discharged fuel may entail high radiological consequences and could give rise to severe deterministic health effects off site. After some time, decay heat may drop significantly with the decay of very short lived radionuclides, but the spent fuel still requires active cooling, and its sabotage may result in doses to persons off site that warrant urgent protective actions.

The facilities used for the storage, management, reprocessing and disposal of SNF need an appropriate level of physical protection, as the possible attack scenarios against SNF storage facilities (unauthorized removal as well as sabotage) could give rise to unacceptable and high radiological consequences and severe deterministic health effects both on site and off site.

The implementation of security systems and measures requires the application of a graded approach based upon the inventory of radioactive material, the ease with which the material can be dispersed, the intrinsic risk of criticality and the irradiation history of the fuel in the facility.

As outlined in the Nuclear Security Series Publications [59–61], the security system needs a careful combination of equipment, personnel, procedures and policies. The security systems may include, but are not limited to, the following:

— Technological measures such as central alarm stations, intrusion detection and assessment systems, barriers, communication systems and search systems;
— Personnel security arrangements addressing the issues of controls over access to different security areas and sensitive information, and insider mitigation programmes.

The security measures are to be applied in a graded manner following the approaches of defence in depth and balanced protection as recommended in the Nuclear Security Series publications [59–61].

7.2. SAFEGUARDS AND ACCOUNTANCY

This section provides an overview of IAEA safeguards approaches and examples of Member States' operational experiences in relation to safeguards implementation.

7.2.1. Consideration of safeguards on the design and operation of a facility

The IAEA implements a set of technical measures, or 'safeguards', to independently verify a State's legal commitment to not divert nuclear material from peaceful nuclear activities. Safeguards serve as an important confidence building measure through which a Member State can demonstrate — and other Member States can be assured — that nuclear material and technology are being used and remain for peaceful purposes [62].

In general terms, safeguards activities are designed to verify a Member State's declarations in accordance with the safeguards agreement concluded between the IAEA and the Member State. There are three types of agreements [62]:

— Comprehensive safeguards agreements concluded with non-nuclear-weapon States parties to the Nuclear Non-Proliferation Treaty and to regional nuclear-weapon-free zone treaties;
— Item specific safeguards agreements currently implemented in three States that are not a party to the Nuclear Non-Proliferation Treaty but undertake not to use nuclear material, facilities or other items subject to the agreement for the manufacture;

— Voluntary offer agreements with the five nuclear-weapon States.

Some of the safeguards verification activities include:

— Design information verification: The IAEA may verify design information prior to construction of a facility commencing, with on-site physical examination throughout construction and subsequent phases of the facility's lifespan.
— Verification of nuclear material inventories and flows: The IAEA evaluates facility records and documentation for consistency with reports submitted by the State. Following the physical inventory of a facility by an operator, the IAEA takes a physical inventory verification to compare results with accounting records. The accounting verification activities are supplemented by surveillance, containment and monitoring activities; these provide additional means to detect access to or undeclared movements of nuclear material.

Irrespective of whether spent fuel is considered to be an asset for recycling or a waste for disposal, from a safeguards perspective it is considered to be a 'direct use material', receiving more attention than fresh fuel.

As spent fuel is relatively difficult and expensive to handle compared to fresh fuel, the transition between the steps of spent fuel management can be considered a one-way flow of material. From an IAEA safeguards perspective, each of the different steps in spent fuel management are considered to be different materials balance areas so that continuity of knowledge can be maintained. Due to the possibility for disassembly and thus eased diversion, locations used for repackaging and associated activities (such as hot cells) are of greater concern for safeguards than storage locations and transfer halls.

Challenges in the safeguards approach for spent fuel include:

— Developing statistically relevant sampling plans;
— Performing non-destructive assay measurements;
— Designing unattended safeguards systems.

These approaches can take into consideration the operator's desire to minimize spent fuel handling and movements. There are a number of safeguards elements that are of particular interest for the management of spent fuel, including:

— Continuous inspection: maintenance of continuity of knowledge relating to the inventory and material flow by witnessing key operations, recording data and data verification.

— Single containment and surveillance system: a configuration in which plausible diversion paths are covered by an IAEA authorized device with established procedures for evaluating the results from the device.
— Dual containment and surveillance system: a configuration as above with at least two systems functionally based on different technology.
— Difficult to access: a designation made by the IAEA Deputy Director General for Safeguards. It can be requested for storage locations that are designed so that it is both difficult to access the contents and easy to detect attempts to access them. As part of this designation, it is important for IAEA verification to address the initial stages of construction.
— Near real time accounting: a form of nuclear material accounting in which the data are maintained by the facility operator and submitted to the IAEA on a near real time basis.
— Inventory mailbox: a location where the facility operator can make inventory or inventory change declarations that are irretrievable and time stamped on a frequent basis; often used in conjunction with near real time accounting.
— Short notice random inspection: inspections performed on both short notice and at a random time.
— Joint use of equipment: safeguards related equipment that can be used by both IAEA and a State actor if the independence of the measurement can be maintained. These arrangements aim to reduce the resources required to support verification activities.

To address verification challenges, IAEA safeguards will continue to evolve. Active research and development are under way to enhance techniques for verifying nuclear material in spent fuel.

One means to address these challenges is by considering safeguards requirements during the design phase of a new facility through safeguards by design [63]. When designing a new storage facility, considering safeguards requirements early in the process can minimize the risks of scope, schedule and budget creep and facilitate integration with other design considerations such as operations, safety and security. Safeguards by design is a voluntary process that encourages the early inclusion of safeguards considerations into the design and construction stages of new facilities. Such an approach can ensure that the facility infrastructure has the flexibility to support current safeguards requirements as well as to accommodate innovations over time. An approach that can accommodate changes allows the use of newer alternatives as they either become available or as older systems become obsolete.

7.2.2. Operational experience with safeguards

This section presents some experiences from the perspective of operators in relation to implementing safeguards in different types of spent fuel storage facilities in various Member States.

7.2.2.1. Japan (dry storage systems)

Dry cask storage facilities in Japan are in operation at Fukushima Daiichi NPP (TEPCO) and Tokai No.2 NPP (JAPC). Their operational experiences of safeguards follow.

(a) TEPCO

Fukushima Daiichi NPP had six BWR power reactors that were shut down following the earthquake and subsequent tsunami in 2011. Spent fuel in the common spent fuel storage facility originally received from the reactor pools has been progressively transferred to an on-site temporary cask custody area since 2013. As of June 2018, 33 metal casks were stored in the temporary cask custody area.

IAEA safeguards inspections have been conducted twice for each cask per movement of the spent fuel from the pool to the temporary cask custody area. During the first inspection, the number and identification of spent fuel assemblies in a cask were confirmed at the common spent fuel storage facility using an underwater camera. After the confirmation, spent fuel assemblies were randomly verified by a Digital Cherenkov Viewing Device. The second inspection involved the attachment of seals to the secondary lid of the casks. In addition, IAEA inspections are carried out once a year for inventory check purposes in order to confirm the number of casks, confirm random seals, replace random seals and verify design information at the temporary cask custody area.

(b) JAPC

The BWR at Tokai No.2 NPP has not operated since the earthquake in 2011. An on-site dry cask storage facility remains in operation and, as of June 2018, stored 21 dry casks.

It receives an IAEA safeguards inspection once a year. The key point of the inspections is to confirm the immobility of the stored casks. Tamper-indicating seals are attached to the casks by the IAEA; the dry casks cannot be moved or opened without breaking the seals. Special attention was paid to the seals when the cask storage area was cleaned of any dust during the operation. Some seals were randomly inspected and replaced by the IAEA.

7.2.2.2. Spain (dry storage systems)

The PWR at Jose Cabrera NPP has an AFR-RS facility hosting 12 HI-STORM systems storing 377 fuel assemblies in total (with 26 of them classified as damaged), equivalent to an inventory of 100 tHM of spent fuel generated by the power plant. Every HI-STORM system consists of a steel lined concrete storage overpack with a welded canister inside to store up to 32 fuel assemblies, up to 45 GWd/tHM and for a minimum of three years cooling.

To comply with regulations, Euratom[22]/IAEA inspection is carried out once per year to check inventory and confirm the number of casks. During these inspections, random verification of the cask seals is undertaken, with some metal seals being randomly replaced. Optical seals can also be replaced if found to be deteriorated. The casks have two types of safeguards seals placed by Euratom and IAEA:

— Seals to guarantee the immobilization of the stored casks;
— Seals to confirm the content of the casks.

IAEA also performs random inspections on interim spent fuel storage facilities with short notice (48 hours) to verify that there is no change at the facilities or in the accountancy. By the end of 2019, Jose Cabrera NPP had received three inspections of this type (2014, 2015, 2019).

At the Jose Cabrera NPP AFR-RS facility, along with the spent fuel systems, there are four HI-SAFE systems storing the highly activated waste coming from dismantled reactor internals (defined as ‘special waste’ in Spanish regulation, similar to Greater Than Class C (GTCC) in US radioactive waste classification). These HI-SAFE systems are a variation of HI-STORM systems adapted for this kind of waste and, in this case, are not subject to safeguards.

For the Centralized Storage Facility (CSF) for spent fuel and high level waste currently in its design phase, the Spanish radioactive waste management agency Empresa Nacional de Residuos Radiactivos S.A. (Enresa) is implementing the safeguards by design concept, following the international guidelines from IAEA and Euratom. The approach is based on the principle that safeguards requirements and objectives are fully integrated into the design process of the

[22] Euratom, the European Atomic Energy Community, is a regional safeguards authority that fulfils the role of a national safeguards authority for EU signatories to the Euratom Treaty.

facility. In this regard, Enresa submitted the basic technical characteristics of the facility to Euratom in July 2014.

7.2.2.3. Sweden (wet storage system)

The system for safeguards control at the Swedish Clab facility (WS1M) comprises key measurement points (KMPs) to determine the flow of nuclear materials and the inventory. For monitoring the flow of nuclear material, there are two KMPs:

— KMP 1 — Reception, for imports into the facility;
— KMP 2 — Dispatch, for exports out of the facility.

For determining the physical inventory, there are four KMPs:

— KMP A — Fuel or fuel residue in storage pools;
— KMP B — Fuel or fuel residue in reception pools;
— KMP C — Dry reception areas;
— KMP D — Other positions for nuclear material in the plant.

The nuclear material held at Clab is in the form of fuel elements and fuel residues that are placed into storage racks after import. Once the storage racks are filled, they are moved into the storage hall.

Clab is subject to physical inspections by IAEA safeguards, and two types of inspection are implemented. The first is a physical inventory verification that is completed each calendar year with a maximum of 14 months between inspections. There is also at least one unannounced inspection each year. During an inspection, Clab will, among other things, show:

— The inventory changes since the last inspection;
— Where the inventory is placed, in list form and on pool maps;
— The weight of the nuclear substance divided by origin.

In terms of reporting, Clab has several reporting lines with different requirements regarding when each must be reported:

— All inventory changes within three working days, to the Swedish Radiation Safety Authority;
— All inventory changes on a monthly basis, to Euratom;
— Total inventory and changes during the year after completion of the physical inventory verification, to Euratom;

— Planning each November for the year ahead to Euratom;
— The status of Japanese steel fuel boxes held each January, to Euratom;
— An update of construction design and any new or demolished buildings, each February to the Swedish Radiation Safety Authority.

8. ECONOMICS OF SPENT FUEL STORAGE

The following section is a summary of information that can be found in the Nuclear Energy Series guide Costing of Spent Fuel Storage [64]. Other studies on cost estimations performed by the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (NEA) can be found in Refs [65, 66].

8.1. COST CATEGORIES AND COMPONENTS

The development of a spent fuel storage facility is implemented over a series of phases covering the life cycle of the project, as reflected in Fig. 54.

For a spent fuel storage facility, the basic categories of cost associated with it that will be incurred over the life cycle are capital, operation and maintenance, decontamination and decommissioning, transport of spent fuel to storage and/or disposition and operational contingencies.

8.1.1. Capital costs

Capital costs are those that are incurred during the design, construction and licensing of the facility. These costs will vary depending on different factors, such as the selected technology, the project schedule and sensitive societal or political

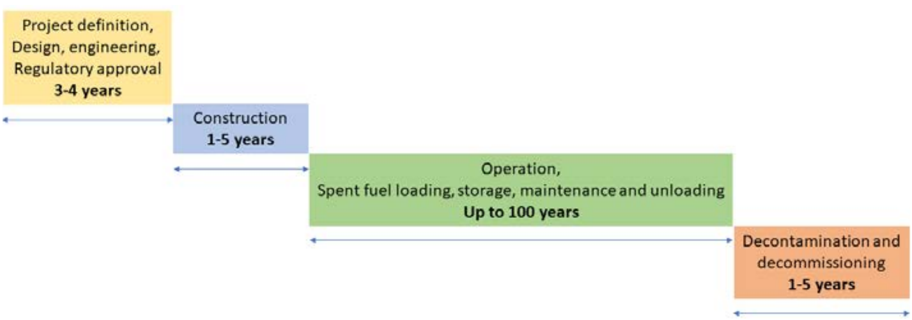

FIG. 54. Life phases of a spent fuel storage facility.

aspects during the licensing process. Capital costs are assumed to be incurred in advance of the facility being used.

8.1.2. Operation and maintenance costs

Operation and maintenance costs occur during the facility lifetime. These costs are dependent on the selected technology and can vary widely depending on whether passive or active management storage systems are used.

8.1.3. Decontamination and decommissioning costs

The cost of decontamination and decommissioning of a storage facility at the end of its operational life need to be estimated. Again, these costs can vary widely depending on the storage technology implemented. The design features of a particular storage system ought to provide for straightforward decommissioning. Since determining the cost of an activity to be implemented 50 years or more into the future may be almost impossible, most regulators request a periodic update (every 3–5 years) of the decommissioning plan and associated cost to ensure that enough financial resources will be available.

8.1.4. Costs associated with the transport of the spent fuel to storage and/or disposition

At some point, the spent fuel will have to be transported off site for disposition. The cost of off-site transportation may therefore have a bearing on the type of off-site facility that is selected as well as its location and infrastructure. Again, these costs may be difficult to determine with any level of accuracy if they are estimated over 50 years in advance.

8.1.5. Costs associated with operational contingencies

It is possible to estimate the costs associated with potential schedule and additional storage capacity delays, changes in regulations, security requirements or implementation of fuel cycle technology advances (such as advanced technology fuel). To manage these uncertainties, a modular approach can be applied to satisfy immediate needs and allow for flexibility for the future. There may also be uncertainties about future maintenance or refurbishment works. While it may be difficult to predict these costs within an uncertain time frame or scope, contingency planning may be a differentiator that informs the choice between particular technologies, so an estimate ought to be developed as part of decision making.

8.2. FACTORS AFFECTING COSTS AND ECONOMICS

The requirements and specifications for a spent fuel storage facility will influence the selection of technology and the associated costs.

8.2.1. Technical factors

The following parameters are those with the most significant implication in the costs of spent fuel storage facilities.

8.2.1.1. Spent fuel characteristics

These are the spent fuel characteristics that are key considerations for storage safety and have the most significant impact on the cost of storage facility design and operation:

— Type of fuel;
— Initial enrichment (fissile content);
— Burnup;
— Thermal load;
— Radionuclide inventory;
— Physical integrity.

8.2.1.2. Functional factors

As well as factors related directly to the characteristics of the spent fuel to be stored, there are functional factors to be taken into consideration.

One such factor is economy of scale. Spreading the fixed cost of a project over a large number of units results in a lower fixed cost per unit, while the recurring cost associated with every unit is not affected. There are a series of considerations that need to be taken into account when determining the effect of scale on the overall cost of the storage system. In general, the largest benefit of scaling is obtained with systems that have higher fixed capital costs. It can be generalized that large fixed capital systems (such as pools and dry storage buildings) generally need to store large volumes of spent fuel (e.g. >600 tHM) in order to be economically justifiable, in the absence of other technical constraints.

A related factor is modularity: smaller modular systems such as casks enable capital expenditure to be spread over time when compared to the upfront expense of a pool, which is beneficial if cash flow is restricted. A modular approach can also provide for flexibility in the future.

The transportability of a system is another factor. Dual and multipurpose systems present benefits in reducing spent fuel handling, minimizing the associated safety risk and reducing interface issues within the spent fuel management system. From a financial perspective, these systems are often more expensive than storage only casks and may be more difficult to design and licence. There may be risk in the ability to transport these packages after long storage times, necessitating long term monitoring and maintenance and potentially repacking at a later date, thereby losing the operational advantages and increasing the cost burden unnecessarily.

8.2.1.3. Conditional factors

These factors relate to the proposed storage site(s) and the conditions and requirements that need to be assessed.

— Site costs, preparation and development;
— Ecological conditions;
— Environmental effects;
— Infrastructure for site access;
— Security implications.

The effects on cost differ between spent fuel storage facilities located AFR-RS and those AFR-OS that are completely independent.

8.2.1.4. Project agenda and time

Given the time frame required for design and licensing of a new storage facility, the project time may in part influence the technology choices made. The development of a facility of an existing type in the country, and therefore already known to the regulator, can usually incur less of a delay than might occur for a wholly new design. The licensing process is usually longer than construction and its associated cost can be significant, therefore its funding has to be secured in advance.

8.2.2. Other factors

In addition to the technical factors, there are other factors that have an influence on the cost and economy of spent fuel storage:

— Technical knowledge, whether the system is first of a kind or widely implemented;

— Procurement and contract strategy;
— Social and political factors;
— Long term institutional issues;
— Risks and uncertainties;
— Availability of construction and manufacturing resource;
— Future inflation and currency exchange;
— Security aspects;
— Final disposition strategy and timing.

8.3. FINANCING

Funding for spent fuel storage, as well as for NPP dismantling and decommissioning and for spent fuel and HLW disposal, has to be collected while the reactors are generating revenue. This is usually via a levy on electricity rates that is collected and invested for those specific activities. The mechanism ought to be in place as soon as possible to facilitate collecting funds as soon as the reactor is connected to the grid. The precise method of fund collection is dependent on the utility or country and its particular business model. Three financing methods are:

— Utility financed: the utility collects funds over the operating period.
— Government funded: funds can be gathered from either the utilities or by appropriation of tax revenue.
— Commercially funded: a non-utility company can finance a storage facility from its own or borrowed funds and charge a fee to the utilities for their services; the utilities may collect this fee from the consumer.

Since spent fuel management up to the point of disposal is a long term task, it is important to assure that the value of the collected funds does not depreciate over time (100 year time frame); there are various options for maintaining the effective value of the funds.

9. ANTICIPATED FUTURE DEVELOPMENTS IN STORAGE

The evolution of spent fuel storage needs to be taken into account in the planning and design of future storage systems and equipment. These include trends towards higher burnup, integration of storage, transport and disposal requirements (if already available at the design stage) into the storage system designs, incorporating safeguards directly into spent fuel storage facility designs, storage systems and packaging, the use of burnup credit or moderator exclusion in demonstrating compliance with subcriticality requirements and recognition of the need to preserve transportability over extended storage periods. The introduction of advanced technology fuels and other new fuels associated with the deployment of small modular reactors also requires consideration.

Until a pathway for disposition of spent fuel is available with sufficient capacity for both present and projected spent fuel inventories, the duration and inventories of spent fuel that need to be accommodated cannot be known. Future technologies, policies, requirements and other factors not presently known will also influence future spent fuel management issues and opportunities.[23]

Given the above, it is difficult to know what future is to be prepared for. Further, a key lesson from the past is that presumptions relative to the timing, pathway and end state for spent fuel have not materialized as they were envisioned. This has resulted in the need to re-evaluate and adjust regulations, licences and designs. Hence, acknowledging, accepting and directly addressing uncertainty relative to future policies and the availability of infrastructure is an essential element for effective planning, design and regulation of future spent fuel storage systems. The planning has to consider a range of possible future scenarios. IAEA Nuclear Energy Series NF-T-3.3, Storing Spent Fuel until Transport to Reprocessing or Disposal [10], provides a number of observations and suggestions for ensuring safe, secure and effective storage in the long term, such as:

— Safe, secure and effective spent fuel storage minimizes fuel degradation while preserving future fuel cycle options;
— Significant cost and risk reduction over the long term can be achieved through the selection process for a storage site, facility type and equipment design;
— Spent fuel storage configurations can be selected and designed with the intention of accommodating uncertain storage periods, facilitating ageing management and providing flexibility to tackle uncertain future end points such as reprocessing or disposal;
— Design of regulatory frameworks facilitates licence renewals to ensure safety over the storage periods;

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[23] Future strategies for the management and disposition of spent fuel may include the implementation of new recycling schemes or the potential for different repository types (such as boreholes or multinational repositories).

— Navigation of the complexity of political systems and societal beliefs and values has proven to be a significant challenge;
— Clear, consistent and stable national policies and strategies are essential for sustainable spent fuel management.

Appendix I

EXAMPLES OF RECENT STORAGE FACILITY DESIGNS

In the first two decades of the 2000s, many new spent fuel storage facilities have been designed, constructed and put into operation. This appendix outlines the principles, rationale and design features of seven storage facilities at varying stages of development across the world at the time of writing.[24]

I.1. CENTRALIZED INTERIM SPENT FUEL WET STORAGE, FRANCE

A centralized wet storage facility for spent fuel as an interim step between AR wet storage facilities and reprocessing at La Hague is planned for implementation.

The French strategy for spent MOX and enriched reprocessed uranium fuels is to safely store them, pending future reprocessing and the potential use in future reactors such as Generation IV reactors. There is a need to extended interim storage capacities as the quantity of non-reprocessed spent fuel slightly increases every year.

To accommodate these accumulated arisings, the French nuclear power company Electricité de France (EDF) submitted the safety option file for a new wet storage facility — the EDF-centralized interim storage pool — to the nuclear safety authority Autorité de sûreté nucléaire in April 2017. This safety file was assessed by the safety authority and its technical support organization, the Institut de Radioprotection et de Sûreté Nucléaire or IRSN. The French advisory committee in charge of fuel cycle facility safety issued its advice and recommendations in January 2019.

I.1.1. Description of design

In continuity with the French fuel cycle, wet storage was selected. Dry storage has been investigated as a contingency to compensate for any difficulties occurring before commissioning of the pool.

The total planned capacity of the storage facility is 10 000 tHM, equivalent to around 21 000 spent fuel assemblies, of mainly MOX and enriched reprocessed

[24] Information regarding the facilities was supplied by Member States in the period 2019–2021.

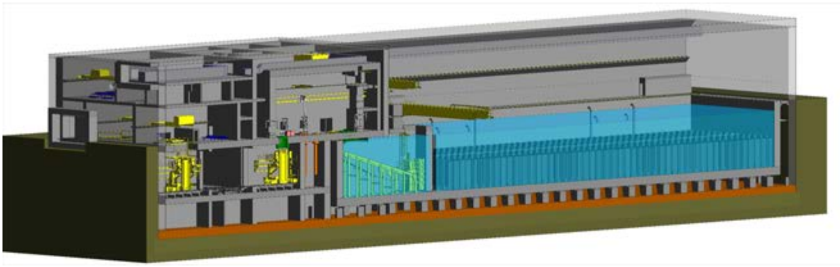

FIG. 55. Centralized interim spent fuel wet storage in France (Courtesy of Electricité de France).

uranium type. It is planned that this storage facility — the outline design is illustrated in Fig. 55 — would be operated for a period of roughly 100 years, starting in 2034.

The facility would be composed of two pools with a water height greater than twice the length of the spent fuel assemblies. The building would be semiburied, and construction could be modular. This facility has to perform four main functions:

— Spent fuel package reception;
— Spent fuel cask preparation and dry unloading;
— Storage of spent fuel and removal from storage;
— Water cooling and treatment.

The main features are two static containment barriers, completed by a dynamic containment that is ensured by a nuclear ventilation system. The concrete pool structure will be coated by a metal liner, and there will be no penetrations under the water level. Subcriticality will be maintained by controlling basket geometry and the use of neutron poisons.

Decay heat removal will be performed by a cooling system with designated redundancy. The external containment barrier will be designed to provide resistance against external aggressions, earthquakes, flooding, climate change evolutions, aircraft crashes and tornadoes. Extreme external aggressions are considered in the DECs.

I.1.2. Status of the facility

This facility is at the design stage as of 2019, with commissioning forecast for 2034.

I.2. INTERIM STORAGE FACILITY FOR SPENT FUEL IN MUTSU, JAPAN

The interim storage facility in Mutsu, Aomori Prefecture, is located in the northern part of the Japanese main island and operated by the Recyclable-Fuel Storage Company (RFS) to store spent fuel from NPPs operated by TEPCO and JAPC. The planned capacity for the facility is ~5000 tU of spent fuel with around 200–300 tU transported there annually. After a period of storage, spent fuel will be transported to the reprocessing plant. The storage period is 50 years for each storage building and 50 years for each cask.

The Japanese national policy is based on reprocessing spent fuel to maximize resource use (from the perspective of recovered plutonium) and reduce the volume and radiotoxicity of HLW [67]. Expansion of the spent fuel storage capacity permits flexibility in achieving this policy while ensuring safety.

I.2.1. Description of design

The dry storage facility will eventually consist of two buildings in which the metal DPCs will be stored (Fig. 56). The first of these storage buildings was designed for 3000 tU (a maximum of 288 metal casks) and has been constructed as shown in Fig. 56. The building occupies a footprint of 131 m × 62 m and is 28 m high. This will be followed by a second building. Rather than using an overhead travelling crane, the DPCs are moved to the storage area using an air pallet transporter. In summary, the major facilities and equipment at Mutsu are:

- Facilities to receive, store and dispatch spent fuel;
- Metal casks (DPCs with a capacity of 69 BWR fuel assemblies, 2.5 m–diameter and 5.4 m length);
- Storage building;
- Cask handling facility;
- Transport road;
- Administrative building.

The specifications of spent fuel to be stored in Mutsu are shown in Table 4. The cask handling is illustrated using a mock-up cask in Fig. 57.

I.2.2. Status of facility

The RFS submitted an application for the establishment permit to operate the RFS Center in March 2007, and it was issued in May 2010 [68]. This was

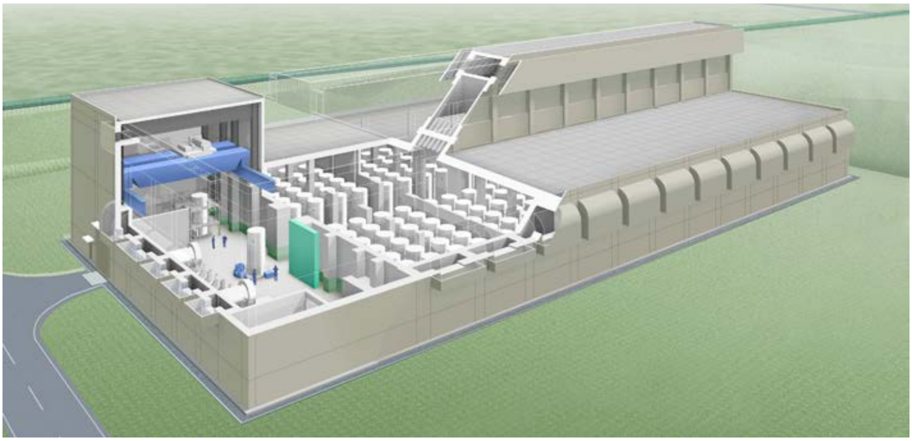

FIG. 56. Image of the Cask Storage Facility in Mutsu (Copyright: RFS 2019. Unauthorized use or reproduction of this image is prohibited).

TABLE 4. SPECIFICATIONS OF THE SPENT FUEL TO BE STORED IN MUTSU (COURTESY OF TEPCO)

Fuel type		New type of 8 × 8 fuel	New type of 8 × 8 zirconium liner fuel	High burnup 8 × 8 fuel
Initial enrichment		~3.1 wt%	~3.1 wt%	~3.7 wt%
Burnup	Avg.	—	34 GWd/t	34 GWd/t
	Max.	34 GWd/t	40 GWd/t	40 GWd/t

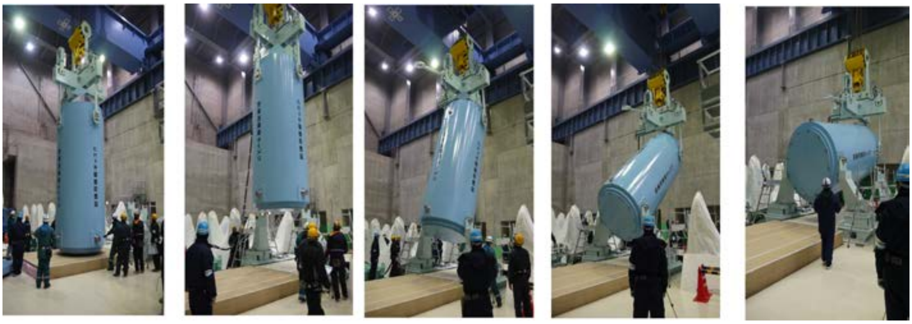

FIG. 57. Cask handling training using a mock-up cask (Copyright: RFS 2019. Unauthorized use or reproduction of this image is prohibited).

followed by an application for the approval of design and construction methods in June 2010 [69].

In December 2013, new regulatory standards based on the lessons learned from the Fukushima Daiichi accident were enforced for all nuclear fuel cycle facilities. The RFS submitted the application to renew the establishment permit to operate the RFS Center to the NRA in January 2014. The RFS has been undergoing NRA review under new regulation standards.

RFS started construction of the storage building and fabrication of the metal casks in August 2010. The building was completed in August 2013, despite a hiatus of around a year following the Great East Japan Earthquake in March 2011. Several metal casks are also being fabricated with various inspections as transport and storage casks.

I.2.3. Operational experience

In preparation for the start of operations, RFS is carrying out cask handling training using a mock-up cask, air pallet transporter, handling equipment and transport vehicle.

I.3. CENTRALIZED DRY STORAGE FACILITY FOR SPENT FUEL AT MINING AND CHEMICAL COMPLEX, RUSSIAN FEDERATION

Two vault type dry storage facilities for spent fuel storage have been constructed and are in operation at the MCC in the Russian Federation; one is for the storage of RBMK spent fuel and the other for WWER-1000. Each facility is planned to store fuel for a period of 50 years, and the total capacity of the storage complex is over 30 000 tHM.

The spent fuel management policy of the Russian Federation is based on a closed cycle. It involves minimization of stored spent fuel through reprocessing and recycling of fissile material to maximize resource utilization and reduce demand for uranium and to ensure minimization of radioactive waste (fission products and minor actinides). It was originally assumed that, after the short (1–3 year) AR storage period, spent fuel would be transported to the reprocessing plant. The absence of a large scale reprocessing capability for WWER-1000 and RBMK spent fuel in the early 2000s led to an increase in the inventory of stored spent fuel, so a centralized facility was implemented at MCC. In practice, a combination of wet and dry technologies is usually implemented. Initially, the newly loaded spent fuel from the reactor is sent to the fuel pools for storage, and then, after a certain storage time, transferred to dry storage. Following a period of storage, spent fuel from WWER and RBMK will then be sent for reprocessing within the integrated complex at MCC.[25]

I.3.1. Description of design

The facility uses dry storage technologies. There are three storage facilities; two storage buildings designed for more than 20 000 tHM of RBMK-1000 and one storage building designed for more than 10 000 tHM for WWER-1000 spent fuel. Each building occupies a footprint of 250 m × 33 m. Fuel is stored within sealed canisters ('penals') installed within two tiers of storage cells ('storage nests'), which are housed in concrete chambers. Each penal holds either:

- 31 ampoules containing bundles of RBMK-1000 fuel elements. The stainless steel non-gas-tight ampoules are received from the NPPs containing cut RBMK fuel assemblies[26] or
- 4 WWER-1000 fuel assemblies.

The removal of residual heat from the spent fuel during storage is achieved by natural air circulation in the storage chambers. Subcriticality, both under normal conditions and in emergency situations, is ensured by controlling mass, enrichment and geometry; a geometrically favourable design maintains strict locations of the spent fuel within the storage area. During long term storage, periodic selective monitoring of the condition of the penals and ampoules containing spent fuel is provided. Defective spent fuel (with damage to the cladding of the fuel rods and a strongly altered geometry) may be accepted only in individual thin-walled canisters sealed by welding.

The dry storage technology used at MCC is based on the passive principle of safety protection; in the event of a loss of power supply, safe conditions will be maintained due to natural convection air cooling. All spent fuel transfer and storage operations are fully automated to exclude the influence of human factors

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[25] A complex of nuclear fuel cycle facilities that integrates storage, reprocessing and recycling is under development at MCC, which will ultimately have the benefit of reducing the transportation of nuclear materials and enabling safety and security measures to be focused at one location. There are existing facilities at the site for SNF storage, fast reactor fuel fabrication and SNF reprocessing. Future facilities at MCC include a regenerated mixture (known as REMIX) fuel fabrication plant and development of molten salt reactors. An underground research laboratory is also under construction at the site to support R&D for the deep geological disposal programme.

[26] RBMK fuel assemblies consist of two elements connected by a tie bar. 'Cutting' the tie bar separates the full assembly into two separate fuel elements.

on safety. The design of the SNF storage and handling system is based on the following main criteria and technical solutions:

- Ensuring worker and public dose remains below limits during both normal operations and DBAs;
- The principle of a multibarrier system for minimizing the potential for release to the environment (fuel pellet, fuel cladding, ampoule or sealed penal, sealed storage cell, building structures of the storage facility);
- Use of technical means aimed at prevention of DBAs and measures limiting the consequences of DECs;
- Equipment and building design that consider potential DBAs scenarios;
- Storage of spent fuel in sealed penals installed two tiers high, sealed in cells by welding after installation of the penals;
- Ensuring subcriticality under normal conditions and in an emergency by a geometrically safe arrangement of the cells (diameter 720 mm with a step of 1000 mm × 1000 mm);
- Ensuring the tightness of the storage cell and detection of any release of radioactivity into the storage cell if the penal system depressurizes, by monitoring the tightness of the storage cell and the penals it contains;
- Ensuring capability to carry out tests, maintenance, dosimetry control and checks for radioactive contamination of equipment involved in the process of storage and handling of spent fuel;
- Accounting and control of the location, quantity and movement of fuel assemblies provided in the processes of loading, storage and transportation of spent fuel.

The facility exterior can be seen in Fig. 58, with a cutaway of the interior shown in Fig. 59.

After an initial test, the cask is placed (via transfer platforms) underneath the socket of the collecting box and sealed once docked. In the hot cell, the penals are loaded with ampoules containing bundles of fuel elements. After the penal charging is complete, it is closed and the cover is welded to its housing. From the hot cell, the leak-tight penals are taken to the refuelling machine. This machine transfers the penals to the storage cell in accordance with the preset coordinates, removes the plug and inserts the penal into the cell. The storage cell is plugged and welded, with the weld joint monitored for leak tightness. After the loading of the penals is completed, the refuelling machine installs the plug and disconnects from the storage cell. Periodic monitoring of gas composition in the cells and penal cell leak tightness is performed in accordance with the schedule and is undertaken using self-moving carriages installed in the assembly hall. If

FIG. 58. General exterior view of the dry RBMK spent fuel storage facility.

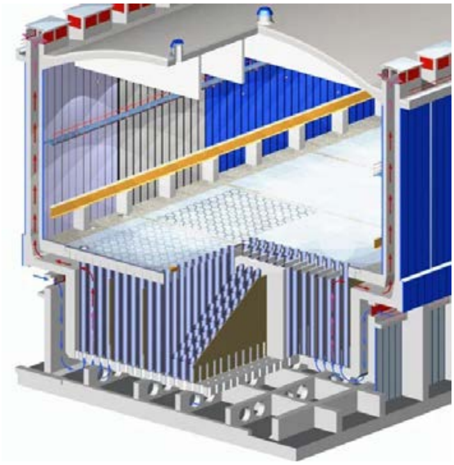

FIG. 59. Section of chamber-type dry storage building for spent fuel storage at the MCC.

any violation of the controllable parameters is detected in the cell, it is opened and the penals are reloaded into another cell. This process is illustrated in Fig. 60.

In summary, the major facilities and equipment associated with the storage facilities at the MCC are:

— Area for loading of transport containers and the traverse travelling platform;
— Hot cell ('collecting box');
— Penal transfer to storage area;
— Spent fuel storage area (separate storage of RBMK and WWER fuels);
— Transport road;

— Administrative building;
— Other necessary infrastructure.

Table 5 shows the specifications of spent fuel stored at the MCC.

I.3.2. Status of facility

The storage facility has been in operation since 2012.

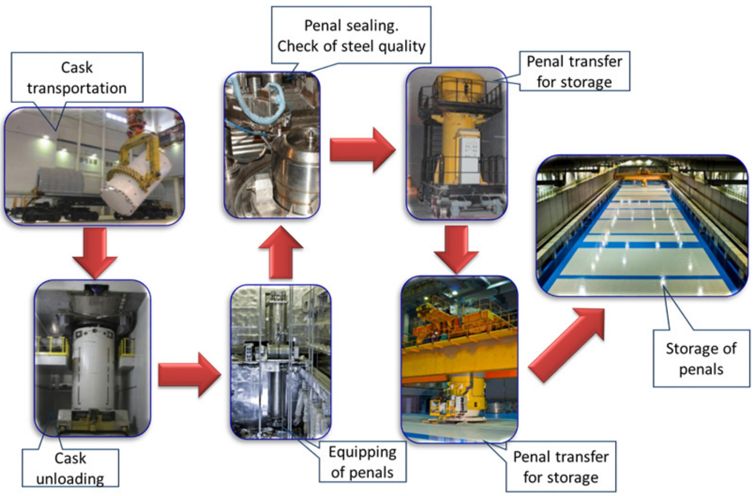

FIG. 60. Steps in spent fuel transfer to dry storage in centralized dry storage in the MCC.

TABLE 5. SPECIFICATIONS OF THE SPENT FUEL STORED IN THE CENTRALIZED DRY STORAGE FACILITY AT THE MCC

Fuel type	RBMK	WWER-1000
Initial enrichment	2.4 wt% (3.2% for U-Er fuel)[a]	Up to ~4.4%[b]
Burnup	Up to 30 GWd/t	Up to 50 GWd/t

[a] Uranium-erbium fuel, in which erbium is a burnable absorber.
[b] Average enrichment.

I.4. CENTRALIZED STORAGE FACILITY, SPAIN

The Spanish CSF is intended to provide safe interim storage for HLW, spent fuel and 'special waste'[27] generated by the Spanish nuclear programme.

In Spain, the management of spent fuel generated at the NPPs is based on an open cycle scenario, with the construction of a national deep geological repository planned in the future. Currently, spent fuel is stored in either AR or AFR-RS facilities. The national policy on the radioactive waste management, established by the successive General Radioactive Waste Plans, considers a centralized solution for the storage of spent fuel, HLW and special waste as the preferred option, based upon considerations of strategic, technical, economic, safety and security factors.

The CSF is considered the most suitable solution to make the temporary management of spent fuel, HLW and special waste independent from disposal. By reducing the number of radioactive waste storage facilities and, therefore, the number of nuclear sites, there would be a corresponding reduction of the risk and burden associated with this type of installation. It would also allow for rationalization and optimization of future operation and necessary support services for radioactive waste management. In addition, there could also be an economic benefit through a reduced cost to overall radioactive waste management.

In any case, the CSF represents an intermediate stage in spent fuel management which would be followed by the development of a deep geological repository for disposal.

I.4.1. Description of design

The CSF is designed to receive, handle and temporarily store an estimated national inventory of ~22 000 spent fuel elements (Table 6); HLW from overseas reprocessing activities (vitrified canisters) and special waste (vitrified and metallic compacted waste from reprocessing activities, waste resulting from NPP decommissioning activities and radioactive encapsulated sources) (Table 7). The lifetime considered for the design is 100 years, with an estimated operational life of 60 years.

The CSF would be a modular vault type where spent fuel and waste is received dry in a hot cell for conditioning. A diagram of the main process is shown in Fig. 61.

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[27] 'Special waste' is the term used for activated components and decommissioning wastes that are unsuitable for disposal through the Spanish low and intermediate level waste routes.

TABLE 6. SPENT FUEL INVENTORY

Spent fuel type	Total fuel assembly estimates (tU)
PWR	12 811 (5846)
BWR	9 125 (1641)
TOTAL	21 936 (7487)

TABLE 7. HLW AND SPECIAL WASTE INVENTORY

	Type	Total
HLW	Canister CSD-V	68
Special waste[a]	Canister CSD-B	12
	Canister CSD-C	12
	Waste from reactor decontamination and decommissioning	458 m^3

[a] Non-fuel hardware and NPP operational wastes are not included.

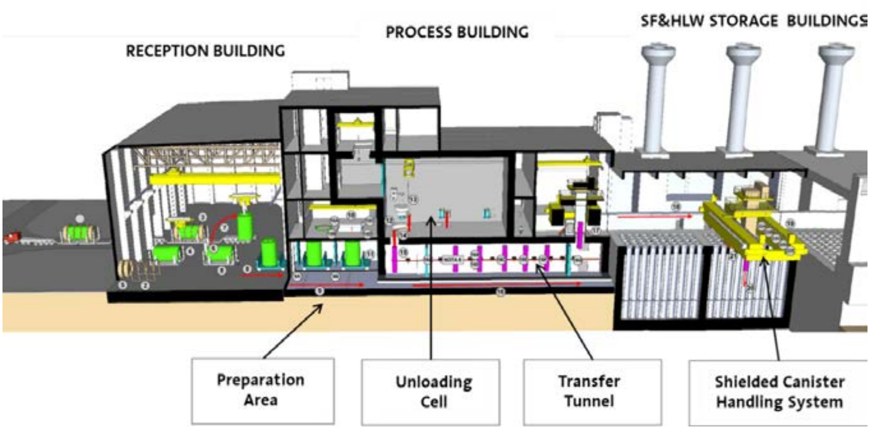

FIG. 61. CSF main process.

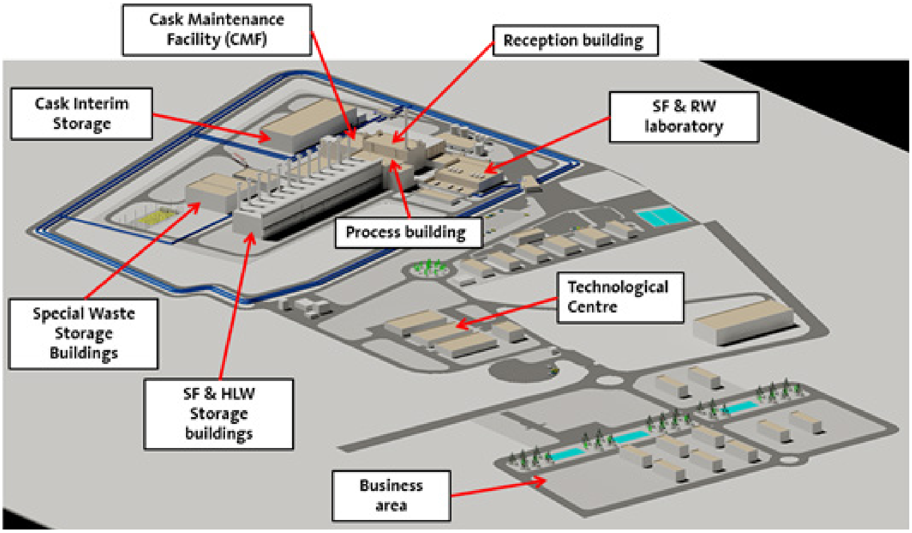

FIG. 62. General CSF layout.

The facility will have a dual function as a storage installation and a radioactive waste management technology and research centre. The storage facility is divided into several buildings (Fig. 62). It includes a buffer storage building to receive and temporarily store up to 78 casks for efficient inflow management. There will also be buildings dedicated to the storage of encapsulated radioactive sources and operational waste, a cask maintenance facility and a parking area. The spent fuel and high level waste laboratory will focus on the study of their mid- to long term behaviour.

The nuclear installation is designed to comply with the following safety functions under normal, off-normal and accident conditions:

— Confinement: double barrier (canister, casks).
— Heat removal: passive by natural convection.
— Criticality: spent fuel elements geometric disposition inside canisters/casks.
— Shielding: reinforced concrete wall thickness and casks.
— Retrievability: cask and canister retrieval.

I.4.2. Licensing process

Licensing of the CSF began in 2014 but was suspended in 2018 following a request of the Secretary of State for Energy to the Nuclear Safety Council to temporarily suspend the issuance of the mandatory report regarding the request for the construction authorization. The purpose of this suspension was to allow the newly incumbent Spanish Government to reassess the project against the latest radioactive waste inventory data. The General Radioactive Waste Plan will be updated to reflect any changes in scenario planning [70].

I.5. EXTERNAL SPENT FUEL STORAGE FACILITY GÖSGEN NPP, SWITZERLAND

The AR spent fuel pool at Gösgen NPP (KKG) has a storage capacity of 656 fuel assemblies. Since fuel reprocessing has been prohibited by the Swiss government, the storage strategy consists of operational wet storage and dry interim storage.

Spent fuel can be transferred from the pool after two years of initial cooling. The external wet storage facility at KKG, an AFR-RS pool, was built to provide additional capacity to support a longer initial cooling time for the fuel and, therefore, more flexibility for transport and storage cask[28] loading optimization. Eventually the spent fuel will be transported to the centralized dry storage facility known as Zwilag.

I.5.1. Description of the facility

The design complies with the regulatory requirements for normal operation, off-normal operation and accident conditions (e.g. earthquake and airplane crash).

The pool, with a height of 12.5 m and an area of 13.2 m × 8.2 m, is stainless steel lined and filled with demineralized water, with a water level of 12 m. Subcriticality is ensured by the use of storage racks with borated stainless steel absorber channels.

The pool cooling system is based on both passive and active systems. It has provision for four cooling loops and uses natural circulation. Natural and forced convection are ensured, the latter by means of fans.

The facility was built with a storage capacity of 1008 spent fuel assemblies. The main characteristics are described in Table 8.

A view inside the external spent fuel pool at KKG is shown in Fig. 63, while Fig. 64 illustrates the completed wet storage facility.

The cooling requirements are derived from German guidance (requirements) given in KTA standard 3303 [71]. Under normal operations, the facility relies entirely on a passive system via natural circulation for cooling of the fuel assemblies. The system is equipped with external cooling fans, if required.

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[28] In Switzerland, DPCs are usually referred to as transport and storage casks, or TSCs.

TABLE 8. SPENT FUEL PARAMETER LIMITS

Fuel	Minimum cooling (years)	Initial enrichment	Maximal burnup (GWd/tHM)
UO_2	3	5% ^{235}U	70
MOX	5	4.8% Pu_{fiss}	60

FIG. 63. Internal view of the SNF pool at KKG, Switzerland.

FIG. 64. Completed wet storage facility at KKG, Switzerland.

For severe accident management, the natural circulation cooling is supported by an additional independent mobile pump) that is integrated into the cooling system.

I.5.2. Status of the facility: siting, licensing and construction

A turnkey contract was signed with AREVA NP (Germany) 5 July 2002 for:

- — Basic and detailed design for mechanical and electrical equipment;
- — Licensing documentation (the responsibility of the licensing process remained with KKG);
- — Commissioning;
- — Approximately 40% of the scope subcontracted to local Swiss companies;
- — Total price roughly broken down as 75% hardware and 25% engineering.

I.5.3. Operating experience

Storage conditions are essentially based on clean water immersion under ‘room temperature’ (up to 45°C) and pressure (atmospheric plus water column of a few metres), which guarantee low pressure inside the fuel rods and, with it, the prevention of possible degradation mechanisms such as creep or DHC.

Possible defects in fuel assemblies that lead to the release of activity would be detected by the installed monitoring system (room and exhaust air monitoring through gamma detectors and alpha-beta aerosol monitoring). The pool water is monitored monthly, and any buildup of caesium or iodine concentrations can be detected.

I.6. INTERIM SPENT NUCLEAR FUEL DRY STORAGE FACILITY, UKRAINE

The interim SNF dry storage facility (ISF-2) was developed to provide long term storage for the spent fuel arisings from the Chernobyl NPP (ChNPP). Construction and commissioning of ISF-2 were necessary to enable decommissioning of the original wet interim storage facility called ISF-1, and to support decommissioning of ChNPP units 1, 2 and 3. The storage duration is considered to be 100 years for planning purposes. In 2016 ChNPP units 1, 2 and 3 were defuelled, and the spent fuel arisings are stored in ISF-1 on the ChNPP site; this amounts to 21 284 spent fuel assemblies of RBMK-1000 type.

The original ISF-2 design was developed in 1999 by Framatome, under the international financial and technical assistance provided to Ukraine on the basis of the 20 December 1995 Memorandum of Understanding between the Governments of the G-7 nations, the European Commission and the Government of Ukraine on the closure of Chernobyl NPP, and the Grant Agreement signed on 12 November 1996 between the European Bank of Reconstruction and Development, the Government of Ukraine and ChNPP as part of the ChNPP Nuclear Safety Project.

The design made provisions for ChNPP spent fuel to be stored in a dry environment in sealed canisters placed inside ventilated concrete modules of the NUHOMS type. The ISF-2 construction activities were started by Framatome in 2000, with commissioning estimated for the third quarter of 2004. However, in 2003 significant design deficiencies were identified that affect reliability and safety, leading to a suspension in construction while design solutions were implemented. According to expert evaluations, construction had been 70% complete. As the contractual parties failed to find acceptable solutions to the problems, SSE ChNPP terminated the contract with the French consortium of AREVA NP (Framatome) in April 2007. The responsibility for design modifications and completion of construction was assumed by Holtec International, which for two years had taken part in the discussion on the technical approaches to resolution of the ISF-2 problems. It was also recognized that the structures already built were of a sufficiently high level of quality and could be used for the technology proposed by Holtec International for the completion of construction.

Although the storage technology was not limited for design proposals, dry storage was selected because it formed the basis of all successful first stage proposals during the tendering process. Evaluations demonstrated that it best met the requirements of ensuring safe and economical operation for 100 years of storage. Holtec International's proposal for completion of ISF-2 uses double wall canisters.

I.6.1. Description of design

ISF-2 is a dry spent fuel storage facility at the ChNPP site. ISF-2 is designed for the processing and interim storage of ChNPP RBMK-1000 SNF after transfer from ISF-1. It consists of two main parts: a spent fuel processing facility and an SNF storage area. An overview of the site is illustrated in Fig. 65.

The total storage capacity of ISF-2 will be 21 297 RBMK-1000 fuel assemblies, with a reception and treatment capacity of 2500 fuel assemblies per year. The storage part is based on the NUHOMS interim dry storage system.

The spent fuel processing facility is intended for the acceptance, 'cutting' and packing of damaged and non-damaged fuel assemblies into double walled canisters, including drying and helium inerting operations. Drying of spent fuel

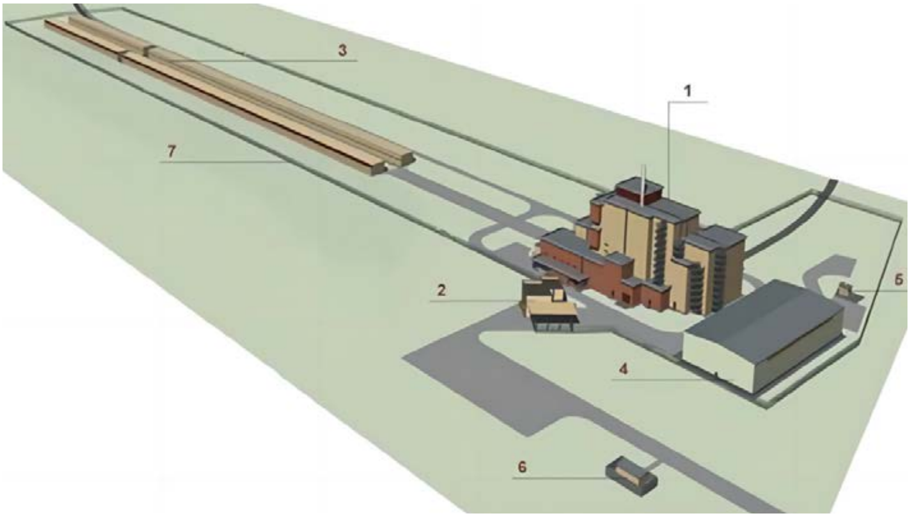

FIG. 65. ISF-2. (1) Spent fuel processing facility; (2) gate house; (3) concrete storage module; (4) cartridges and cases warehouse; (5) sewage pump station; (6) station ARMS; (7) fence. (Image credit: Technical Report: Overview of Ukrainian Regulatory Framework and Practices on Spent Fuel Management. SSTC NRS. Kyiv, 2018.)

assemblies is crucial, as the increased water content in the sealed canisters could potentially cause increased concentrations of water in the canister, leading to increased internal pressure above the limit and presenting a risk of rupture of the canister body. Additionally, the presence of water vapours in the fuel storage environment increases the risk of corrosion and formation of explosive mixes as a result of the radiolysis process. The spent fuel processing facility will also accept, package and store absorber rods and extension rods.

The storage area consists of transport and technological equipment used to handle the canisters and 58 horizontal concrete storage modules. The modules are built in two rows of 29 modules — A and B — facing each other across a central aisle ~9.5 m wide. Each module includes four storage cells, each accommodating one canister containing spent fuel. The canisters consist of an enclosure vessel comprising two welded canisters forming two separate confinement areas to prevent the spread of radioactive materials, and an internal basket. Decay heat removal will be performed by natural convection through the concrete module.

Figure 66 shows the facilities and canisters used in the packaging and storage process.

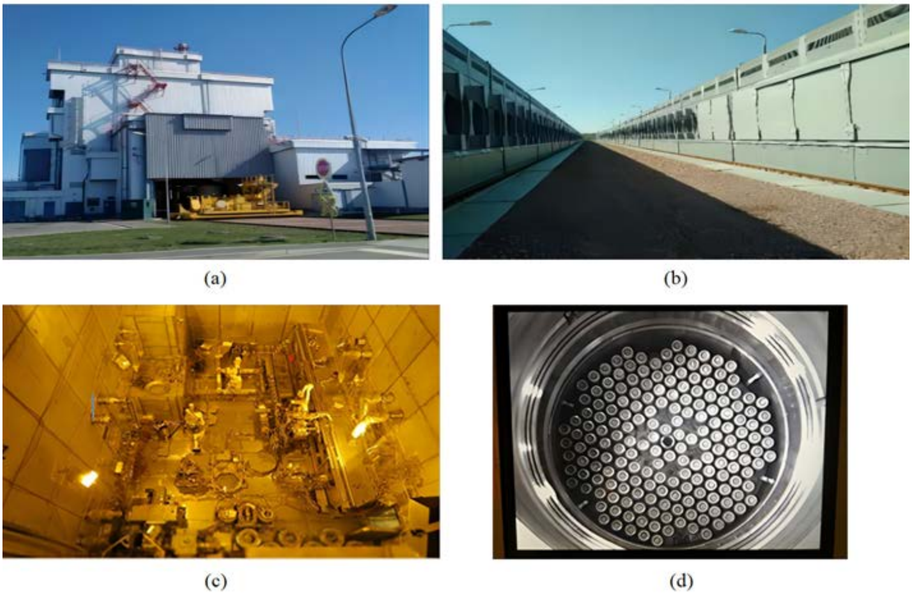

FIG. 66. (a) Installation ISF-2 for spent fuel preparation for storage, (b) spent fuel storage area, (c) hot cell (d) doublewalled canister containing spent fuel assemblies.

I.6.2. Status of the facility

'Cold' tests of the facility were completed in a three stage process. The first stage tested the major process systems using dummy fuel assemblies. The second stage tested auxiliary systems and the third stage focused on the maintainability of ISF-2 equipment (i.e. the feasibility of remote repair of components in case of failure.

On 10 September 2020, SSE ChNPP began work and operations in the framework of an ISF-2 'hot' test. During 'hot testing', according to the programme, 186 spent fuel assemblies will be transferred from the current ISF-1 to the ISF-2. Following completion of required technological operations, the canisters containing the spent fuel assemblies will be placed into the concrete ISF-2 storage modules.

I.7. BELOW GRADE DRY SPENT FUEL STORAGE SYSTEM, SAN ONOFRE, USA

San Onofre NPP (SONGS) is located on the Californian coastline, meaning that both the marine environment and seismic activity of the area had to be taken into consideration when selecting an AFR design. For the second independent spent fuel storage installation (sometimes abbreviated to ISFSI) at the site, the UMAX system was selected.[29] The below grade HI-STORM UMAX system was designed for high seismic resistance. Development work between the utility and vendor led to the use of a laser peening process on the stainless steel storage canisters to further protect them from corrosion by the marine air.

The UMAX system design provides shielding and physical protection to reduce worker exposure, meaning that no dosimetry is required to access the SONGS UMAX independent spent fuel storage installation. The NPP site has a relatively small footprint and is in close proximity to a publicly accessible footpath, making this level of shielding a desirable attribute. The UMAX system can be seen in Fig. 67 along with the original TN NUHOMS system. Figure 68 shows a schematic of the canisters inside the system.

The MPC-37 multipurpose canister (MPC) licensed for storage in the UMAX system has been approved by the Nuclear Regulatory Commission for

FIG. 67. SONGS TN NUHOMS (left) and Holtec UMAX (right) Storage Systems. (Courtesy of SCE.)

[29] A TN NUHOMS system was used for storage of fuel from SONGS units 1, 2 and 3.

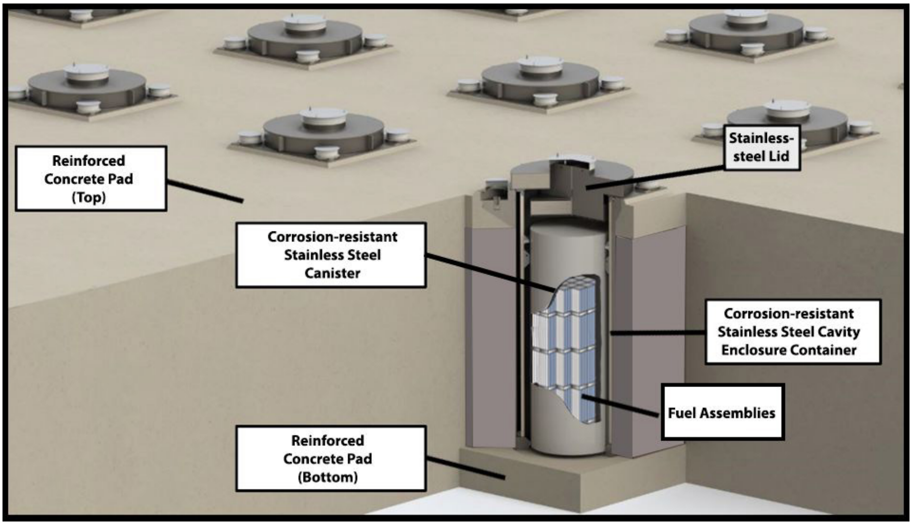

FIG. 68. Internal and external structure of a UMAX system. (Courtesy of SCE.)

transportation in the HI-STAR 190 cask; this approval includes transportation of high burnup fuel.

I.7.1. Description of the facility

Combustion engineering 16 × 16 PWR fuel is stored in the UMAX system at SONGS. The maximum fuel burnup is 55.1 GWd/tU, with a maximum enrichment of 4.64 wt%. The MPCs are licensed for the storage of damaged fuel, as authorized by Certificate of Compliance 72-1040.

I.7.2. Status of the facility: siting, licensing and construction

The SONGS site included three operating reactors:

— Unit 1: a Westinghouse design PWR operated from 1968–1992. The reactor has been decommissioned, with all above ground facilities removed and the spent fuel placed into dry storage in a NUHOMS system.
— Units 2 and 3: Combustion Engineering design PWRs operated from 1983–2012. Spent fuel from these units is stored in the NUHOMS and UMAX systems.

The UMAX system is located on the SONGS site. Construction commenced in 2016, and loading operations began in 2018. The final fuel transfer took place in August 2020 to enable decommissioning of Units 2 and 3 to commence.

I.7.3. Operating experience

Defuelling of the Units 2 and 3 AR pools into the UMAX system was carried out between 2018–2020.

On 3 August 2018, an MPC became wedged on a shield ring internal to the storage module during placement into the UMAX storage module. This condition was not recognized by the loading crew as it happened, and they continued to lower the vertical cask transporter towers into the fully downloaded position. This resulted in a condition in which the lifting slings were completely slack, creating the potential for the MPC to drop approximately 5.5 m (18 feet) to the bottom of the storage module. This condition was quickly discovered and corrected by the loading crew. A subsequent cause evaluation led to improved procedures and oversight, improvements in the corrective action and training programmes and equipment enhancements. Canister loading resumed in July of 2019. Figure 69 shows an illustration of the incident.

In March and April of 2019, eight MPCs were visually inspected to address an inconsistency between the UMAX safety analysis report and field observations. The safety analysis report stated that there was no risk of scratching MPCs due to ample clearances, contrary to field observations made of MPC-to-storage module contact. The inspections found minimal canister shell wear due to

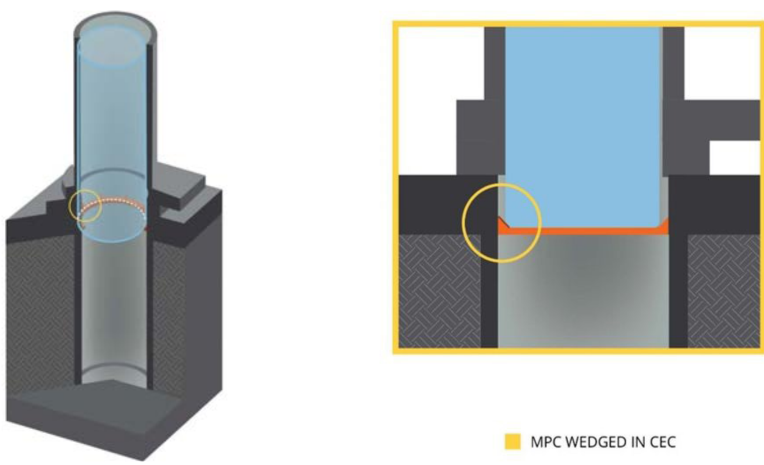

FIG. 69. MPC wedged on shield ring inside the cavity enclosure container. (Courtesy of SCE.)

FIG. 70. Inspections of UMAX MPC system at SONGS: inspection crew set-up (left) and robot with high-resolution camera deployed inside of the UMAX storage module (right). (Courtesy of SCE.)

interaction with internal components of the storage module, well below the level allowable by the ASME Code. With the storage module lid removed, the entire canister shell was accessible by the robot and camera, except for the bottom 2.5 cm (1 inch), which was occluded by the pedestal upon which the MPC rests. Figure 70 shows work under way during the inspections.

Appendix II

REGULATIONS AND GUIDANCE FOR SPENT FUEL STORAGE AND TRANSPORT

Regulation and guidance are provided at both an international level and a national level. The following sections provide a summary of the relevant IAEA regulations and guidance as well as regulations and guidance provided by other international bodies and national regulatory authorities.

II.1. IAEA REGULATIONS AND GUIDANCE RELATED TO SPENT FUEL STORAGE

As illustrated in Fig. 71, the IAEA Safety Standards provide the fundamental principles, requirements and recommendations to ensure nuclear safety (see Appendix V for those relevant to spent fuel storage). There are three tiers of publications:

— Safety fundamentals: establish the fundamental safety objective and principles of protection and safety.

FIG. 71. IAEA Safety Standards hierarchy.

— Safety requirements: set out the requirements that must be met to ensure protection of people and the environment now and in the future.
— Safety guides: provide recommendations and guidance on how to comply with the requirements.

II.2. RELEVANT REGULATIONS OR GUIDANCE BY OTHER INTERNATIONAL BODIES

II.2.1. Recommendations of the International Commission on Radiological Protection

The International Commission on Radiological Protection is an independent, international non-governmental organization with a mission to provide recommendations and guidance on radiological protection for ionizing radiation. IAEA takes account of these recommendations when developing safety standards.

II.2.2. EU directives and reports

Council Directive 2011/70/Euratom on the management of SNF and radioactive waste [72] establishes a community framework for ensuring responsible and safe management of spent fuel to avoid imposing undue burdens on future generations.

II.2.3. Western European Nuclear Regulators' Association

The Western European Nuclear Regulators' Association issues safety reference levels for numerous areas, including radioactive waste and SNF storage [73]. The safety reference levels build upon the essential basis of safety established by the IAEA Safety Standards and offer more facility specific requirements for developing national regulations. These levels focus on four different areas of safety: safety management, design, operation and safety verification.

II.3. NATIONAL REGULATIONS AND GUIDES ON SPENT FUEL STORAGE AND TRANSPORTATION

All countries have national regulations and guides. Examples are given in Table 9.

TABLE 9. EXAMPLES OF NATIONAL REGULATIONS AND GUIDES BY MEMBER STATES

Member State	Regulation / guide	Ref.
France	IRSN 2019-00181 Storage of nuclear spent fuel: concepts and safety issues (June 2018)	[74]
	IRSN 2019-00903 Assessment of dry storage possibilities for MOX or enriched reprocessed uranium spent fuels (April 2019)	[75]
Germany	ESK Guidelines for dry cask storage of spent fuel and heat-generating waste (revised version of 2013-06-10)	[76]
Japan	Ordinance on Activity of Interim Storage of Spent Fuel, Ministry of Trade, Economy, and Industry, revised by Nuclear Regulation Authority (2014)	
	Statement on dry cask on-site storage of spent fuel, Nuclear Safety Commission of Japan (1992, revised in 2006)	
UK	NS-TAST-GD-081 (Rev. 3) Safety Aspects Specific to Storage of Spent Nuclear Fuel, ONR, Bootle (June 2019)	
USA	NUREG-2215 — Standard Review Plan for Spent Fuel Dry Storage Systems and Facilities (2020)	[19]
	NUREG-2214 — Managing Ageing Processes in Storage (MAPS) Report (2019)	[77]
	NUREG-1927 — Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel (Rev. 1, 2016)	[55]
	Spent Fuel Storage and Transportation Interim Staff Guidance, Nuclear Regulatory Commission (web site)	[78]

II.4. REGULATIONS FOR SPENT FUEL TRANSPORT

SNF has been safely and routinely transported for over 60 years, covering a distance of millions of kilometres without any significant incidents. Spent fuel transportation is carried out within the international regulatory framework based upon the IAEA Regulations for the Safe Transport of Radioactive Material, first

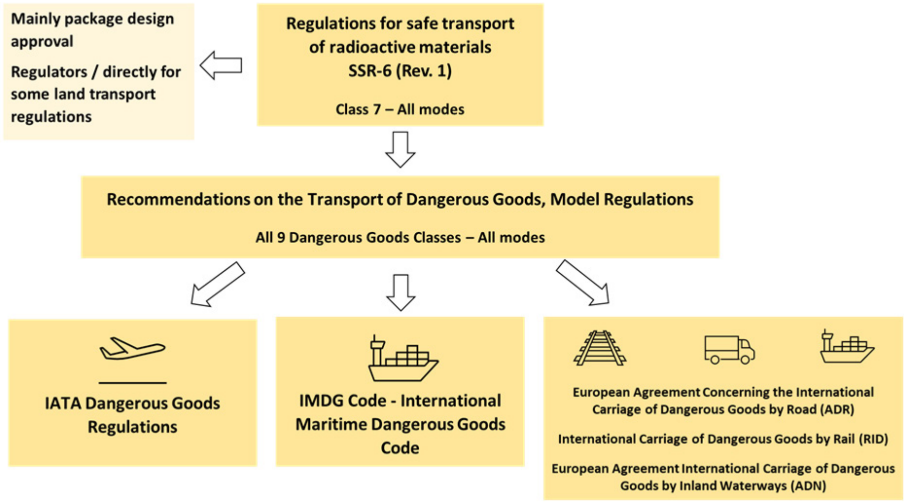

FIG. 72. The connections within the international transport safety regulatory framework.

published in 1961 and periodically revised. These regulations ensure safety and protect people, property and the environment from harmful effects of ionizing radiation during the transport of radioactive material. The current edition was published in 2018 and is identified as SSR-6 (Rev. 1) 2018 edition [50]. Figure 72 shows the international transport safety regulatory framework.

For radioactive material, the transport safety regulatory requirements are set out in the IAEA Regulations for the Safe Transport of Radioactive Material, SSR-6 [50], which are adopted into the United Nations Model Regulations [79] for radioactive material and classified as Class 7 dangerous goods.

The United Nations Model Regulations are subsequently adopted into the global transport regulations' International Maritime Dangerous Goods Code [80] for transport of radioactive material by sea, and the International Civil Aviation Organization Technical Instructions [81] for transport by air. These two documents are mandatory in all States.

There are no global land transport regulations, however. To create a globally consistent set of transport safety regulatory requirements, States create and implement national land transport regulations that reflect SSR-6 requirements, while a small number of States adopt SSR-6 directly.

Regional agreements based on the United Nations Model Regulations are also created, with the example of the European agreements for transport by road [82], rail [83] and inland waterways [84] which are mandatory for States that are signatories to those agreements.

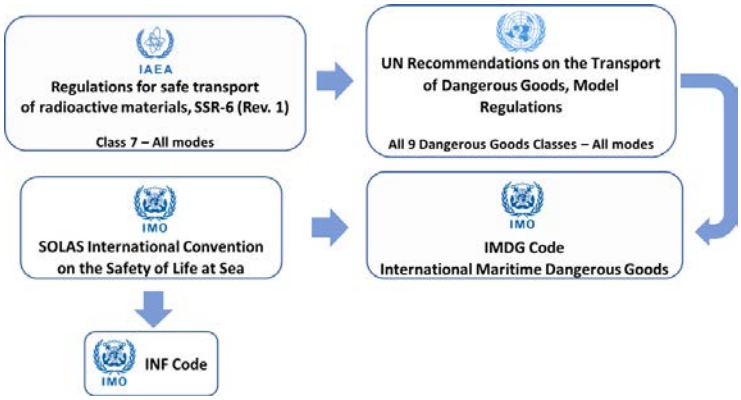

FIG. 73. The International transport safety regulatory framework for transport by sea.

The transport regulations for the transport of radioactive material by sea make a distinction in the requirements for SNF from other radioactive material as shown in Fig. 73.

The International Convention for the Safety of Life at Sea, the SOLAS Convention [85], Part-A, Regulation 3, requires the carriage of dangerous goods in packaged form to be in compliance with the International Maritime Dangerous Goods Code. The code for radioactive material, Class 7 dangerous goods, reflects the SSR-6 requirements that spent nuclear reactor fuel is to be transported in a Type B fissile package design that meets prescribed requirements and performance testing criterion. In addition, the SOLAS Convention Chapter VII, Part D, prescribes other requirements for spent nuclear fuel, namely:

— Regulation 14 defines SNF as 'INF Cargo'. INF cargo includes irradiated nuclear fuel, plutonium and high-level radioactive wastes.
— Regulation 16 states that a ship carrying 'INF Cargo' needs to comply with the requirements of the INF Code[30] adopted by the Maritime Safety Committee of the International Maritime Organisation by resolution MSC.88 (71) [86].

[30] The term INF Code refers to the International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes On-Board ships. According to Regulation 15, the INF Code does not apply to warships, naval auxiliary or other vessels owned by a contracting government and used on government non-commercial service.

Appendix III

EXAMPLES OF DESIGN BASIS ACCIDENTS RELATED TO SPENT FUEL HANDLING

Some examples of possible handling accidents during the operation of a storage facility are identified below. Handling accident events are not limited to the examples given below but address all credible and required accident scenarios.

III.1 EXAMPLES OF POSTULATED WET STORAGE HANDLING ACCIDENTS

During spent fuel handling in the pool, the following potential drop events are traditionally evaluated:

— Fuel drops could cause damage to the fuel;
— Fuel dropped adjacent to spent fuel storage racks could also impact the effective neutron multiplication factors[31] (K_{eff}) of the adjacent racks;
— Fuel dropped onto a spent fuel rack could also damage the rack.

For each of these cases, the most unfavourable reactivity configuration that is reasonably possible is to be considered and evaluated and compared with acceptable K_{eff} limits. Fuel retrievability associated with drop scenarios also needs to be addressed.

III.2 EXAMPLES OF POSTULATED DRY CASK STORAGE HANDLING ACCIDENT EVENTS

Cask drop and cask tipover are the handling accident events generally considered in the spent fuel cask design. These are described below.

III.2.1. Cask drop

The design documentation has to identify not just the drop event that could occur (i.e. vertical, horizontal or corner, as shown in Fig. 74), but also the

[31] A K_{eff} value of less than one means that a system cannot sustain a neutron chain reaction and therefore remains subcritical.

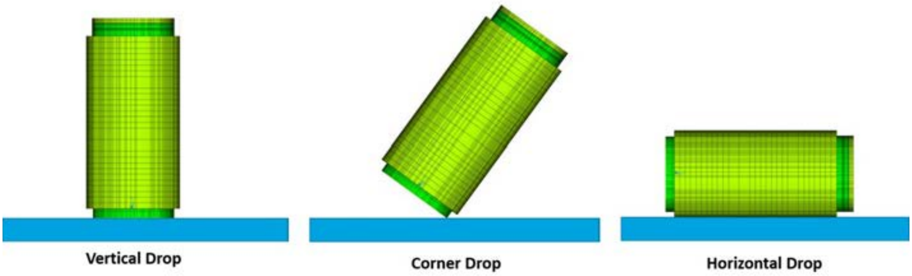

FIG. 74. Three types of cask drop. (Courtesy of David Garrido.)

operating environment experienced by the cask. Either the maximum cask lift height or the maximum acceleration that could be experienced in a drop event are generally used to establish the design basis [87].

III.2.3. Cask tipover

The analysis of cask tipover events is deemed by most regulators to be worthy of investigation, despite the identification of cask system supporting structures as being important to safety and designed to preclude such an event. Cask tipover may be determined as a credible hazard in some cases, so the conditions associated with a tipover event, such as heights and accelerations, need to be reflected in the analysis. The analysis can be undertaken using analytical means and/or prototype or scale model tests, with an unyielding surface generally being accepted [87].

Generally, these accidents are evaluated through analyses using finite element methods with explicit algorithms. Stress and strain limits are based on accepted design codes (i.e. ASME (USA) RCCM (France) KTA (Germany) JSME (Japan)). Cask safety related functions, such as structural, confinement, criticality and fuel integrity, are within design code limits.

These design basis conditions establish an operating envelope that ensures safety is maintained under the full range of plausible conditions. For example, the establishment of a design basis drop enables the maximum lift height of the cask to be defined within the design and licensing documentation by the applicant, thereby identifying the operational envelope where no additional safety analysis or design changes (e.g. addition of impact limiters) are required [87].

Appendix IV

REPORTED MATERIALS PERFORMANCE DATA

A large amount of research results and operational performance data are available for storage system materials. Such information has been collated from numerous sources and is presented in Table 10.

TABLE 10. REPORTED PERFORMANCE DATA FOR MATERIALS USED IN SPENT FUEL STORAGE SYSTEMS

Material	Measured/calculated property	Test conditions	Degradation mechanism being measured	Comment	Ref.
Carbon steels	A. 5 µm/yr (metal loss)	Pool water (A, B in open pools)	General or uniform corrosion	A. Typical demineralized pool water pH 5–7 (good quality water)	[38]
	B. 200 µm/yr (metal loss)			B. In high chloride pool water (760 ppm)	
	C. 100 µm/yr (metal loss)			C. For zinc coated carbon steel in pool water (with 760 ppm chloride)	
Steel (carbon, low-alloy, high strength alloy)	0.2 mm/yr (metal loss)	Atmospheric conditions	General or uniform corrosion	Rate of corrosion for untreated steels exposed to external atmospheres (rate of corrosion in heavily polluted atmosphere is higher)	[77]
Steel (carbon, low-alloy, high strength alloy)	Up to 0.2 mm/yr (0.01 mm/yr) (metal loss)	Groundwater/soil aerobic (anaerobic)	Microbial induced corrosion	Buried pipes	[77]

TABLE 10. REPORTED PERFORMANCE DATA FOR MATERIALS USED IN SPENT FUEL STORAGE SYSTEMS (cont.)

Material	Measured/calculated property	Test conditions	Degradation mechanism being measured	Comment	Ref.
Stainless steel (304, 304L, 316L)	A. 0.01–0.1 µm/yr (metal loss)	A. Pool water demineralized	General/uniform corrosion	A. Test facility pool water tested for 18 months	[16, 31, 32, 38]
	B. 0.3 µm/yr (metal loss)	B. Storage pool water, demineralized water with up to 7.5 ppm chloride		B. Open storage pool	
	C. <0.1 µm/yr (metal loss)	C. Storage pool water, demineralized with sodium hydroxide dosed to pH11.4		C. Gas reactor storage pool	
Stainless steel pool liner	A. 0.03 µm/yr (metal loss)	Pool water, demineralized water,	General	A. 304 L determined through water analysis	[31]
	B. <0.05 µm/yr (metal loss)	20–30°C, pH5–6, <300 µS/m		B. ANSI 321 corrosion coupons measured over 15 years	[9]

TABLE 10. REPORTED PERFORMANCE DATA FOR MATERIALS USED IN SPENT FUEL STORAGE SYSTEMS (cont.)

Material	Measured/calculated property	Test conditions	Degradation mechanism being measured	Comment	Ref.
Stainless steel canister	Crack growth rates from 0.1 mm/yr to 0.67 mm/yr	Marine air environment	Stress corrosion cracking	Through-wall penetration during the 60 year time frame	[77]
Iron	A. 0.1 mm/yr (metal loss)	A. Stagnant fresh water	General/uniform		[77]
	B. 10 µm/yr (metal loss)	B. Buried in soil			
Ductile cast iron	0.1 mm/yr (metal loss)	Saltwater	General	Non-protected, equilibrium rate of corrosion	[16]
Aluminium	20–2 µm (total metal loss for surface areas 100–1000 cm^2)	Residual moisture in an inert atmosphere for T >230°C (cask storage)	General/uniform	Bounding calculation. N.B. the figure quoted is total metal loss based on there being 1 L of water present.	[77]
	0.25 µm/yr	Fuel storage pools (<50°C)	General/uniform	Low-conductivity water (<5 µS/cm)	[38]

TABLE 10. REPORTED PERFORMANCE DATA FOR MATERIALS USED IN SPENT FUEL STORAGE SYSTEMS (cont.)

Material	Measured/calculated property	Test conditions	Degradation mechanism being measured	Comment	Ref.
	25 µm/yr (metal loss in marine air environment)	Dry storage, high salt environments (e.g. coastal)	Pitting	Potential for attack of aluminium heat shield on cooling (ventilated dry storage systems)	[77]
	1.3 mm/yr (metal loss in 1M NaCl)	High salt environments (e.g. coastal)	Crevice	Potential for attack of aluminium heat shield on cooling (ventilated dry storage systems)	[77]
	0.2 mm/yr (metal loss for aluminium in contact with carbon steel; SS expected to be higher)	High salt environments (e.g. coastal)	Galvanic	Aluminium plates/seals in contact with stainless steel	[77]

TABLE 10. REPORTED PERFORMANCE DATA FOR MATERIALS USED IN SPENT FUEL STORAGE SYSTEMS (cont.)

Material	Measured/calculated property	Test conditions	Degradation mechanism being measured	Comment	Ref.
	T >200°C (on set for hardened aluminium alloys; series 6000)	High temperatures and stresses	Creep/thermal ageing	Potential for conditions to develop where aluminium is used in structural components in proximity to spent fuel. It is estimated that conditions could prevail for up to 30 years and designs need to take this into account.	[77]
Metals	Carbon steel $>10^{19}$ n/cm^2; Stainless steel $>10^{20}$ n/cm^2; Borated stainless steel $>10^{17}$ n/cm^2; Al $>10^{21}$ n/cm^2; Ni alloys $>10^{20}$ n/cm^2; Cu $>10^{18}$ n/cm^2.	Neutron damage to cask components before a loss in mechanical properties	Radiation induced degradation	N.B. For comparison the accumulated neutron source term for 40, 70 GWd/tHM, 4% ^{235}U, 17×17 PWR fuel assemblies in a dry storage cask over 100 years is 2.63×10^{16} n/cm^2	[77]

TABLE 10. REPORTED PERFORMANCE DATA FOR MATERIALS USED IN SPENT FUEL STORAGE SYSTEMS (cont.)

Material	Measured/calculated property	Test conditions	Degradation mechanism being measured	Comment	Ref.
Concrete	$<10^{19}$ n/cm^2	Neutron damage before a loss in mechanical properties	Radiation induced degradation	N.B. For comparison the accumulated neutron source term for 40, 70 GWd/tHM, 4% ^{235}U, 17×17 PWR fuel assemblies in a dry storage cask over 100 years is 2.63×10^{16} n/cm^2	[77]
Epoxy liner coating	1×10^6 Gy maximum dose operating limit	Pool water (up to 32°C)	Radiation induced degradation	CANDU experience	[12]
Vyal resin	~2.5% (weight loss)	Heating at 160°C for 10 000 hours	Thermal degradation	Neutron shielding materials	[9]
Polyester	>4% (weight loss)	Heating at 160°C for 10 000 hours	Thermal degradation	Neutron shielding materials	[9]
Ethylene rubber	~3% (weight loss)	Heating at 160°C for 10 000 hours	Thermal degradation	Neutron shielding materials	[9]

TABLE 10. REPORTED PERFORMANCE DATA FOR MATERIALS USED IN SPENT FUEL STORAGE SYSTEMS (cont.)

Material	Measured/calculated property	Test conditions	Degradation mechanism being measured	Comment	Ref.
Polyvinyl-chloride	2×10^4 Gy maximum dose operating limit	Demineralized water at 35°C (simulated pool water)	Radiation induced damage	Loss of mechanical strength, test results 1×10^6 Gy (moderate to severe damage), 5×10^6 Gy (degraded). Operating limit based upon order of magnitude safety margin to take account of low dose effects.	[9]
Seals e.g. Viton, nitrile, neoprene, EPDM	0.5–1×10^6 Gy maximum dose operating limit	Materials aged up to 31 years	Radiation induced damage	Tensile strength, elongation & modulus results provided in reference	[41]
Concrete	~1.2 kg/m^3 (concentration of chloride required to attack the reinforcement bar)	Laboratory test of concrete samples in 10% sodium chloride solution	General/uniform/ pitting of encased reinforce-ment bar	Diffusion coefficient is dependent on temperature and the water–cement ratio	[9]

Note: This table is a collection of performance data reported in the literature. Refer to the referenced sources for more detailed information or to elaborate on any inconsistencies or questions.

Appendix V

SPENT FUEL STORAGE RELATED IAEA PUBLICATIONS

This Appendix provides a summary of the publications produced within the IAEA related to spent fuel storage (Table 11).

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE

Area/reference	Scope
	Spent fuel storage
INTERNATIONAL ATOMIC ENERGY AGENCY, Storage, Handling and Movement of Fuel and Related Components at Nuclear Power Plants, Technical Reports Series No. 189, IAEA, Vienna (1979).	This technical report describes in general terms the various operations involved in the handling of fresh fuel, irradiated fuel, and core components such as control rods, neutron sources, burnable poisons and removable instruments. It attempts to outline the principal safety problems in these operations and provides the broad safety criteria that must be observed in the design, operation and maintenance of equipment and facilities for handling, transferring and storing nuclear fuel and core components at nuclear power reactor sites.
INTERNATIONAL ATOMIC ENERGY AGENCY, Storage of Water Reactor Spent Fuel in Water Pools, Technical Reports Series No. 218, IAEA, Vienna (1982).	This publication summarizes the results of a survey conducted by the IAEA and the NEA on the wet storage experiences of water reactor fuel among countries with operating nuclear power programmes. The responses represented over 85% of the water cooled power reactor pools and AFR pools that had operated for 5 years or more. Responses from research reactor pools and facilities that store gas reactor fuel were also included.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Spent Fuel Dry Storage Concepts: Concerns, Issues and Developments, IAEA-TECDOC-359, IAEA, Vienna (1985).	This publication provides the reader with a general understanding of the various dry storage concepts and the facilities required to support them. The outstanding technical concerns relating to dry storage installations as well as demonstration programmes are briefly described. Such other activities as the development and approval of a design criteria standard are presented. A review of the cost of the various concepts is included.
INTERNATIONAL ATOMIC ENERGY AGENCY, Long Term Wet Spent Nuclear Fuel Storage (Proc of a Technical Committee Meeting, Leningrad, 26–30 May 1986), IAEA-TECDOC-418, IAEA, Vienna (1987).	This publication discusses the positive experience in wet spent fuel storage, in upgrading of the existing pools and in the technology to discuss available information on the behaviour of used fuel assemblies in different conditions, the reliability of structural materials, purification and heat removal systems, methods of environment monitoring and control.
INTERNATIONAL ATOMIC ENERGY AGENCY, Behaviour of Spent Fuel Assemblies During Extended Storage (Final Report of a Co-ordinated Research Programme on BEFAST, Phase 1, 1981–1986), IAEA-TECDOC-414, IAEA, Vienna (1987).	This publication is the final report of the IAEA Coordinated Research Programme on Behaviour of Spent Fuel Assemblies During Extended Storage (BEFAST, Phase I, 1981–1986). It contains the results on wet and dry spent fuel storage technologies obtained from 11 institutes in 10 countries participating in the BEFAST coordinated research project.
INTERNATIONAL ATOMIC ENERGY AGENCY, Survey of Experience with Dry Storage of Spent Nuclear Fuel and Update of Wet Storage Experience, Technical Reports Series No. 290, IAEA, Vienna (1988).	This report contains data on dry and wet storage, including spent fuel monitoring, experience on spent fuel behaviour, performance of facilities and test programmes as well as aspects related to rod consolidation, safety, physical protection, regulations and safeguards.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Decontamination of Transport Casks and of Spent Fuel Storage Facilities (Proc. of a Technical Committee Meeting, Vienna, 4–7 April 1989), IAEA-TECDOC-556, IAEA, Vienna (1990).	The objective of this publication was to review the state of the art of technology and practice in the field of decontamination of transport casks and of spent fuel storage facilities and to formulate recommendations for international cooperation. The publication provides an analysis of the technical papers presented at the topical technical meeting held in Vienna, in April 1989, as well as a summary of the panel discussion.
INTERNATIONAL ATOMIC ENERGY AGENCY, Methods for Expanding the Capacity of Spent Fuel Storage Facilities (Proc. of a Technical Committee meeting, Vienna, 12–15 June 1989), IAEA-TECDOC-559, IAEA, Vienna (1990).	The purpose of this publication was to include available information at the international level related to the expansion of storage capacities for spent fuel, to elaborate the state of the art of this topic, and to give recommendations to potential users for selection and application of the most suitable methods for expanding spent fuel facilities, taking into account the relevant country's conditions.
INTERNATIONAL ATOMIC ENERGY AGENCY, Guidebook on Spent Fuel Storage — 2nd edn, Technical Reports Series No. 240, IAEA, Vienna (1991).	This guidebook provides a summary of the experience and information in many areas related to spent fuel storage, including spent fuel storage technology, transport of spent fuel, economics of spent fuel storage, regulatory, institutional and safety aspects, as well as factors used in evaluating spent fuel storage options.
INTERNATIONAL ATOMIC ENERGY AGENCY, Guidebook on Non-destructive Examination of Water Reactor Fuel, Technical Reports Series No. 322, IAEA, Vienna (1991).	The guidebook gives a complete survey of non-destructive techniques available for application in the spent fuel pool as well as in hot cells.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Extended Storage of Spent Fuel (Final Report of a Co-ordinated Research Programme, (BEFAST-II), 1986–1991), IAEA-TECDOC-673, IAEA, Vienna (1992).	This publication is the final report on the IAEA Coordinated Research Programme on the Behaviour of Spent Fuel and Storage Facility Components during Long Term Storage (BEFAST-II, 1986–1991). It contains the results on wet and dry spent fuel storage technologies obtained from 16 organizations representing 13 countries (Argentina, Canada, Finland, Germany, Hungary, Italy, Japan, the Republic of Korea, Sweden, the UK, the USA and the USSR (at that time)), which participated in the coordinated research programme.
INTERNATIONAL ATOMIC ENERGY AGENCY, Away-from-Reactor Storage Concepts and their Implementation, IAEA-TECDOC-759, IAEA, Vienna (1994).	This publication contains the summary of the Technical Committee Meeting on Away-from-Reactor (AFR) Storage Concepts and their Implementation, held in Vienna in 1994, and papers presented during this meeting. The meeting gathered representatives of most of the countries operating NPPs to discuss four issues related to AFRs: the status of AFR; AFR technology evaluation and selection criteria; anticipated developments; possible international activities on AFR storage of spent fuel and initiatives of IAEA on this subject.
INTERNATIONAL ATOMIC ENERGY AGENCY, Remote Technology Related to the Handling, Storage and Disposal of Spent Fuel, IAEA-TECDOC-842, IAEA, Vienna (1995).	This publication contains the papers presented during the IAEA Technical Committee Meeting on Remote Technology Related to the Handling, Storage and/or Disposal of Spent Fuel, held in Albuquerque, New Mexico, USA, 5–8 December 1994, covering the following areas: the choice of remote technologies; the use of remote technologies in fuel handling; the use of remote technologies for fuel inspection and characterization; remote maintenance of facilities; and status and projected developments.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Further Analysis of Extended Storage of Spent Fuel, IAEA-TECDOC-944, IAEA, Vienna (1997).	This publication is the final report of the IAEA Coordinated Research Programme on the Behaviour of Spent Fuel Assemblies During Extended Storage (BEFAST-III, 1991–1996). It contains analyses of wet and dry spent fuel storage technologies obtained from 16 organizations representing 13 countries (Canada, Finland, France, Germany, Hungary, Japan, the Republic of Korea, the Russian Federation, Slovakia, Spain, Sweden, the UK and the USA), which participated in the coordinated research programme as participants or observers.
INTERNATIONAL ATOMIC ENERGY AGENCY, Durability of Spent Nuclear Fuels and Facility Components in Wet Storage, IAEA-TECDOC-1012, IAEA, Vienna (1998).	This publication provides quantitative and semi-quantitative data on materials behaviour or references sources of data to address the wide range of materials issues that can be faced by decision makers and wet storage facility operators. This publication was a product of the coordinated research project on Irradiation Enhanced Degradation of Materials in Spent Fuel Storage Facilities.
INTERNATIONAL ATOMIC ENERGY AGENCY, Technologies for Gas Cooled Reactor Decommissioning, Fuel Storage and Waste Disposal, IAEA-TECDOC-1043, IAEA, Vienna (1998).	The publication provides an overview of decommissioning and associated spent fuel storage and radioactive waste disposal programmes and issues related to gas cooled reactor plants including facilities sharing common technological aspects such as other types of reactors which have graphite moderators.
INTERNATIONAL ATOMIC ENERGY AGENCY, Spent Fuel Storage and Transport Cask Decontamination and Modification, IAEA-TECDOC-1081, IAEA, Vienna (1999).	This publication is a compilation of international experience with cask contamination problems and decontamination practices. Its objective is to represent the knowledge and experience in this field. The annexes contain figures of several cask types for illustration.
INTERNATIONAL ATOMIC ENERGY AGENCY, Survey of Wet and Dry Spent Fuel Storage, IAEA-TECDOC-1100, IAEA, Vienna (1999).	The scope of this publication is to review the technology for storage of spent fuel from power reactors. Countries' experience with spent fuel wet and dry storage as well as for transportation of spent fuel is included.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Multi-purpose Container Technologies for Spent Fuel Management, IAEA-TECDOC-1192, IAEA, Vienna (2001).	The purpose of this publication is to review the status of dual purpose and multi-purpose containers and considerations for their implementation, design and operation. Examples of representative container designs are provided in the appendix.
INTERNATIONAL ATOMIC ENERGY AGENCY, Long Term Storage of Spent Nuclear Fuel — Survey and Recommendations, IAEA-TECDOC-1293, IAEA, Vienna (2002).	This publication addresses the trends in spent fuel storage for extended duration and the related potential technological and regulatory effects. The content covers an overview of the global spent fuel storage, technical issues associated with wet and dry storage, research and development related aspects as well as regulatory aspects.
INTERNATIONAL ATOMIC ENERGY AGENCY, Effects of Radiation and Environmental Factors on the Durability of Materials in Spent Fuel Storage and Disposal, IAEA-TECDOC-1316, IAEA, Vienna (2002).	This is the second publication that addresses results from the coordinated research project on Irradiation Enhanced Degradation of Materials in Spent Fuel Storage Facilities (the first being IAEA-TECDOC-1012). It addresses results of topical studies that are relevant to issues important to materials behaviour in wet storage technology but also involves topics on materials behaviour in dry storage and repository environments, including effects of radiation.
INTERNATIONAL ATOMIC ENERGY AGENCY, Spent Fuel Performance Assessment and Research, IAEA-TECDOC-1343, IAEA, Vienna (2003).	The publication provides an overview of technical issues related to spent fuel wet and dry storage and summarizes the objectives and major findings of research, carried out within the framework of the coordinated research project on Spent Fuel Performance Assessment and Research SPAR.
INTERNATIONAL ATOMIC ENERGY AGENCY, WWER-440 Fuel Rod Experiments Under Simulated Dry Storage Conditions, IAEA-TECDOC-1385, IAEA, Vienna (2004).	The aim of this publication is to provide an insight into the maximum WWER-440 spent fuel cladding temperature at the beginning of placement in a dry storage facility, in the context of the pre-cooling time. This TECDOC contains the results of pre-characterization of the rods, descriptions of the tests and the results of characterizations in the two principal temperature regimes.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Technical, Economic and Institutional Aspects of Regional Spent Fuel Storage Facilities, IAEA-TECDOC-1482, IAEA, Vienna (2005).	This publication addresses the technical, economic and institutional aspects of regional spent fuel storage facilities on the basis of the results of a series of meetings on this topic with participants from IAEA Member States.
INTERNATIONAL ATOMIC ENERGY AGENCY, Understanding and Managing Ageing of Material in Spent Fuel Storage Facilities, Technical Reports Series No. 443, IAEA, Vienna (2006).	This publication contains results from the Coordinated Research Project on Ageing of Materials in Spent Fuel Storage Facilities. It includes sections on the status of the understanding of the ageing of selected materials and on management of ageing. It also includes a brief section on specific approaches in the context of fuel storage facilities, and some specific recommendations. Moreover, the content has been broadened to try to appeal to those who may be in the early stages of setting up ageing management programmes.
INTERNATIONAL ATOMIC ENERGY AGENCY, Selection of Away-from-Reactor Facilities for Spent Fuel Storage, IAEA-TECDOC-1558, IAEA, Vienna (2007).	This publication is intended to provide a review of the key factors associated with selecting from options for AFR facilities for spent fuel storage, together with a discussion of the generic methodology for the decision making, thereby providing guidance on practical approaches to project implementation.
INTERNATIONAL ATOMIC ENERGY AGENCY, Operation and Maintenance of Spent Fuel Storage and Transportation Casks/ Containers, IAEA-TECDOC-1532, IAEA, Vienna (2007).	This publication provides a comprehensive review of information on the cask operation and maintenance associated with spent fuel storage. It draws upon generic knowledge from industrial experience and applications and is intended to serve as a basis for better planning and implementation in related projects.
INTERNATIONAL ATOMIC ENERGY AGENCY, Optimization Strategies for Cask Design and Container Loading in Long Term Spent Fuel Storage, IAEA-TECDOC-1523, IAEA, Vienna (2007).	This publication outlines the optimization process for cask design, licensing and utilization, describing three principal groups of optimization activities in terms of relevant technical considerations such as criticality, shielding, structural design, operations, maintenance and retrievability.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Spent Fuel Performance Assessment and Research Final Report of a Coordinated Research Project (SPAR-II), IAEA-TECDOC-1680, IAEA, Vienna (2012).	This publication presents the results of an IAEA coordinated research project on SPAR-II and contains useful information on the integrity and degradation of spent fuel during storage. The experience and insights gathered facilitates identifying challenges in implementing long term storage and provides an understanding of the status of spent fuel performance research related to long term storage.
INTERNATIONAL ATOMIC ENERGY AGENCY, Spent Fuel Storage Operation-Lessons Learned, IAEA-TECDOC-1725, IAEA, Vienna (2013).	This publication collects the experiences of Member States in the design, construction and operation of spent fuel storage facilities. It collates the improvements which have been incorporated into the design of new storage facilities over the past fifty years, highlights good operating practices and designs and shares lessons learned. The information provided will assist those Member States that already have a developed storage capability and also those considering development of a SNF storage capability in making informed decisions when managing their SNF.
INTERNATIONAL ATOMIC ENERGY AGENCY, Spent Fuel Performance Assessment and Research – Final Report of a Coordinated Research Project on Spent Fuel Performance Assessment and Research (SPAR III) 2009–2014, IAEA-TECDOC-1771, IAEA, Vienna (2015).	This publication provides an update on national spent fuel management strategies, spent fuel and system performance in wet and dry storage, and national research and development activities relating to spent fuel storage. It contains useful information on hydride reorientation and the impact of fuel, storage system components, emerging issues on very long term storage, and the storage of metal fuel in a closed system. The experience and insights provided by the participating countries will help Member States to identify challenges in implementing long term storage and to understand the status of spent fuel performance research related to long term storage.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Evaluation of Conditions for Hydrogen Induced Degradation of Zirconium Alloys during Fuel Operation and Storage. Final Report of a Coordinated Research Project 2011–2015, IAEA-TECDOC-1781, IAEA, Vienna (2015).	This publication summarizes the research work undertaken as part of an IAEA coordinated research project on evaluation of conditions for hydrogen induced degradation of zirconium alloys during fuel operation and storage and includes details of the experimental procedures to evaluate the threshold condition for DHC that led to the production of a set of data for these materials.
INTERNATIONAL ATOMIC ENERGY AGENCY, Storing Spent Fuel until Transport to Reprocessing or Disposal, IAEA Nuclear Energy Series NF-T-3.3, IAEA, Vienna (2019).	This publication identifies issues and challenges relevant to the development and implementation of options, policies, strategies and programmes for ensuring safe, secure and effective storage of spent fuel until transport for reprocessing or disposal. The target audience includes policy and decision makers who need to be aware of the implicit risks and costs associated with decision timing for determining and implementing an end point for spent fuel management (such as reprocessing or disposal) to ensure the responsible and sustainable use of nuclear energy. The publication will assist those within the nuclear industry in communicating the importance of a clear, credible and sustainable spent fuel management strategy and will encourage decision makers to consider different approaches that may be useful in addressing the uncertainties resulting from an unknown storage duration and an undefined end point for spent fuel management.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Demonstrating Performance of Spent Fuel and Related Storage System Components during Very Long Term Storage Final Report of a Coordinated Research Project, IAEA-TECDOC-1878, IAEA, Vienna (2019).	This publication summarizes the work carried out during an IAEA coordinated research project on safe and reliable management of SNF and contributes to the overall goal of demonstrating the performance of SNF and related storage systems components over long durations and facilitates the transfer of this knowledge to Member States. The technical areas addressed by the project participants were related to potential degradation mechanisms in metal casks and concrete overpacks, such as SCC, long term integrity and performance of the fuel cladding, thermomechanical behaviour of the metal seals and long term gamma and neutron shielding capability.
INTERNATIONAL ATOMIC ENERGY AGENCY, Behaviour of Spent Power Reactor Fuel during Storage Extracts from the Final Reports of Coordinated Research Projects on Behaviour of Spent Fuel Assemblies in Storage (BEFAST I–III) and Spent Fuel Performance Assessment and Research (SPAR I–III) — 1981–2014, IAEA-TECDOC-1862, IAEA, Vienna (2019).	This publication consolidates the findings from the BEFAST and SPAR series of coordinated research projects undertaken between 1981 and 2014 and compiles all relevant information in one referenceable source. The technical information provided in this publication will be particularly useful for experts engaged in safety assessments.
INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Safety of Nuclear Fuel Cycle Facilities. INPRO Manual, IAEA-TECDOC-1903, IAEA, Vienna (2020).	This publication provides guidance for assessing the sustainability of a nuclear energy system in the area of nuclear fuel cycle facility safety. It deals with nuclear fuel cycle facilities that may be potentially involved in the nuclear energy system such as mining, milling, refining, conversion, enrichment, fuel fabrication, spent fuel storage and spent fuel reprocessing facilities.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Methodology for a Safety Case of a Dual Purpose Cask for Storage and Transport of Spent Fuel, IAEA-TECDOC-1938, IAEA, Vienna (2020).	This publication provides practical advice on the structure and contents of a dual purpose cask integrated safety case with reference to existing IAEA requirements relevant to the licensing and use of transport and storage casks for spent fuel.
INTERNATIONAL ATOMIC ENERGY AGENCY, Spent Fuel Performance Assessment and Research, Final Report of a Coordinated Research Project (SPAR-IV), IAEA-TECDOC-1975, IAEA, Vienna (2021).	This publication provides an overview of the technical issues related to wet and dry storage of spent fuel. It is based on results obtained in the participating Member States during an IAEA coordinated research project on spent fuel and storage system performance.
Safety standards, guides and reports (storage and transportation)	
INTERNATIONAL ATOMIC ENERGY AGENCY, Fundamental Safety Principles, Safety Fundamentals, Safety Standards Series No. SF-1, IAEA, Vienna (2006).	This publication states the fundamental safety objective and ten associated safety principles, and briefly describes their intent and purpose. These are applicable, as relevant, throughout the entire lifetime of all facilities and activities, including spent fuel storage, existing and new, used for peaceful purposes and to protective actions to reduce existing radiation risks.
INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of Radioactive Waste, General Safety Requirements Part 5, GSR Part 5, IAEA, Vienna (2009).	This Safety Requirements publication presents international consensus requirements for the management of radioactive waste prior to its disposal. It provides the safety imperatives on the basis of which facilities can be designed, operated and regulated. Predisposal management of radioactive waste, as the term is used in this Safety Requirements publication, covers all the steps in the management of radioactive waste from its generation up to disposal, including processing (pre-treatment, treatment and conditioning), storage and transport.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Nuclear Installations, Safety Guide, Safety Standards Series No. GS-G-3.5, IAEA, Vienna (2009).	This Safety Guide has been issued in support of the Safety Requirements publication on the Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-R-3. It contains detailed recommendations in relation to nuclear installations, to complement the general recommendations provided in IAEA Safety Standards Series No. GS-G-3.1. This Safety Guide is applicable throughout the lifetime of a nuclear installation.
INTERNATIONAL ATOMIC ENERGY AGENCY, Criticality Safety in the Handling of Fissile Material, Specific Safety Guide, Safety Standards Series No. SSG-27, IAEA, Vienna (2014).	This Specific Safety Guide provides guidance and recommendations on how to meet the relevant requirements for ensuring subcriticality when dealing with fissile material and for planning the response to criticality accidents. This requirement applies to large commercial facilities, such as nuclear facilities that deal with the supply of fresh fuel, with the management of spent fuel and with radioactive waste containing fissile nuclides, including the handling, processing, use, storage and disposal of such waste.
INTERNATIONAL ATOMIC ENERGY AGENCY, Ageing Management for Nuclear Power Plants: International Generic Ageing Lessons Learned (IGALL), Safety Reports Series No. 82, IAEA, Vienna (2015).	This publication provides a common internationally agreed basis on what constitutes an acceptable AMP, as well as a knowledge base for ageing management for the design of new plants as well as design and safety reviews, and aims to serve as a road map to available information on ageing management. It addresses ageing management of passive and active structures and components for water moderated reactors that can have an effect, directly or indirectly, on the safe operation of the plant and that are susceptible to ageing degradation. The information provided is relevant for plants under normal operation, for plants considering long term operation, as well as for new plants including new designs.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment for Facilities and Activities, General Safety Requirements, No. GSR Part 4 (Rev. 1), IAEA, Vienna (2016).	This publication describes the generally applicable requirements to be fulfilled in safety assessments for facilities and activities, with special attention paid to defence in depth, quantitative analyses and the application of a graded approach to the range of facilities and activities that are addressed. A review of Safety Requirements publications was commenced in 2011 following the accident in the Fukushima Daiichi NPP in Japan. This review covered, among other topics, the regulatory structure, emergency preparedness and response and nuclear safety and engineering aspects (site selection and evaluation, assessment of extreme natural hazards, including their combined effects, management of severe accidents, station blackout, loss of heat sink, accumulation of explosive gases, the behaviour of nuclear fuel and the safety of spent fuel storage).
INTERNATIONAL ATOMIC ENERGY AGENCY, Leadership and Management for Safety, General Safety Requirements, No. GSR Part 2, IAEA, Vienna (2016).	This Safety Requirements publication establishes requirements that support Principle 3 of the Fundamental Safety Principles in relation to establishing, sustaining and continuously improving leadership and management for safety and an integrated management system. These requirements apply to types of facilities and activities that give rise to radiation risks, including facilities for the storage of SNF.
INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Fuel Cycle Facilities, Specific Safety Requirements, No. SSR-4, IAEA, Vienna (2017).	This Safety Requirements publication establishes a basis for safety and for safety assessment at all stages in the lifetime of nuclear fuel cycle facilities. A broad scope of requirements is established for site evaluation, design, construction, commissioning, operation and preparation for decommissioning that must be satisfied to ensure safety. These requirements apply to facilities for conversion, enrichment, nuclear fuel production, storage of fresh and spent fuels, reprocessing, preparation for disposal and associated research and development facilities.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Regulations for the Safe Transport of Radioactive Material, Specific Safety Requirements, Safety Standards Series No. SSR-6 (Rev.1), 2018 Edition, IAEA, Vienna (2018).	This publication is the latest edition of IAEA Safety Standards Series No. SSR-6, Regulations for the Safe Transport of Radioactive Material. The regulations apply to the transport of radioactive material by all modes on land, water or in the air, including transport that is incidental to the use of the radioactive material. Transport comprises all operations and conditions associated with and involved in the movement of radioactive material. These include the design, manufacture, maintenance and repair of packaging and the preparation, consigning, loading, carriage including in-transit storage, unloading and receipt at the final destination of loads of radioactive material and packages.
INTERNATIONAL ATOMIC ENERGY AGENCY, Storage of Spent Nuclear Fuel (Specific Safety Guide), Safety Standards Series No. SSG-15 (Rev. 1), Vienna (2020).	This publication is a revision by amendment of IAEA Safety Standards Series No. SSG-15 and provides recommendations and guidance on the storage of SNF. It covers all types of storage facility and all types of spent fuel from NPPs and research reactors. It takes into consideration the longer storage periods beyond the original design lifetime of the storage facility that have become necessary owing to delays in the development of disposal facilities and the reduction in reprocessing activities. It also considers developments associated with nuclear fuel, such as higher enrichment, MOX fuels and higher burnup. Guidance is provided on all stages in the lifetime of a spent fuel storage facility, from planning through siting and design to operation and decommissioning.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Design of Fuel Handling and Storage Systems for Nuclear Power Plants, Safety Standards Series No. SSG-63, Vienna (2020).	This Safety Guide provides recommendations on how to meet the requirements of IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design, in relation to fuel handling and storage systems. The publication addresses the design aspects of handling and storage systems for fuel that remain part of the operational activities of a nuclear reactor. It covers the following stages of fuel handling and storage in an NPP: receipt, storage and inspection of fresh fuel before use and transfer of fresh fuel into the reactor; removal of irradiated fuel from the reactor and transfer of the irradiated fuel to the spent fuel pool; and reinsertion of irradiated fuel from the spent fuel pool into the reactor. Recommendations are also provided on the storage, inspection and repair of irradiated or spent fuel in the spent fuel pool and the preparation for the removal of this fuel from the spent fuel pool and on the handling of fuel casks in the spent fuel pool and on their transfer.
INTERNATIONAL ATOMIC ENERY AGENCY, Methodology for a Safety Case of a Dual Purpose Cask for Storage and Transport of Spent Fuel. Report of a WASSC/TRANSSC Joint Working Group, IAEA-TECDOC No. 1938, Vienna (2020).	This publication provides practical advice on the structure and contents of a DPC integrated safety case with reference to existing IAEA requirements relevant to the licensing and use of transport and storage casks for spent fuel.
	Safety glossary
INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary, Terminology Used in Nuclear Safety and Radiation Protection, 2018 Edition, IAEA, Vienna (2019).	The IAEA Safety Glossary defines and explains technical terms used in the IAEA Safety Standards and other safety related IAEA publications and provides information on their usage. This is a new edition of the IAEA Safety Glossary, which was originally issued in 2007. It has been revised and updated to take into account new terminology and usage in safety standards issued between 2007 and 2018.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
International conferences on spent fuel management	
INTERNATIONAL ATOMIC ENERGY AGENCY, Safety and Engineering Aspects of Spent Fuel Storage (Proc. of an International Conference in Vienna, 10–14 October 1994), IAEA, Vienna (1995).	Proceedings of a symposium jointly organized with NEA in Vienna on 10–14 October 1994. The purpose of the symposium was to provide an opportunity for the exchange of information on the state of the art and the prospects of spent fuel storage, to discuss the worldwide situation and the major factors influencing the national policies in this field and to identify the most important directions that national efforts and international cooperation in this area should take.
INTERNATIONAL ATOMIC ENERGY AGENCY, Storage of Spent Fuel from Power Reactors (Proc. of a symposium in Vienna, 9–13 November 1998), IAEA-TECDOC-1089 (1999).	This symposium provided an opportunity to exchange information on the state of the art and prospects of spent fuel storage, to discuss the worldwide situation and the major factors influencing the national policies in this field and to identify the most important directions that national efforts and international cooperation in this area should take.
INTERNATIONAL ATOMIC ENERGY AGENCY, Storage of Spent Fuel from Power Reactors, (Proc. of an International Conference, Vienna, Austria, 2–6 June 2003), IAEA, Vienna (2003).	The International Conference on Storage of Spent Fuel from Power Reactors provided an opportunity for exchange of information on the state of the art and prospects of spent fuel storage, for discussion of the worldwide situation and the major factors influencing the national policies in this field and for the identification of the most important directions that national efforts and international cooperation in this area should take.
INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Spent Fuel from Nuclear Power Reactors, (Proc. of an International Conference in Vienna, Austria, 19–22 June 2006), IAEA, Vienna (2007).	This conference addressed recent policy issues, in particular multinational approaches and international cooperation, in spent fuel management including advanced fuel cycles. It also included the discussion of an international safety regime, an assessment of safety issues related to criticality safety and burnup credit, and the issues involved in the long term licensing of storage facilities for spent fuel. The technical issues related to spent fuel storage were also addressed, including issues related to the storage facility, storage containers and fuel.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Spent Fuel from Nuclear Power Reactors, (Proc. of an International Conference in Vienna, Austria, 31 May–4 June 2010), IAEA, Vienna (2015).	This publication presents the proceedings of an international conference on spent fuel management organized by the IAEA in cooperation with the NEA. The conference covered a broad range of topics from national strategies through safety and regulatory aspects, transport, technical innovation, fuel and material behaviour, operational experience with storage, new fuel and reprocessing developments and long term storage and disposal.
INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Spent Fuel from Nuclear Power Reactors: An Integrated Approach to the Back End of the Fuel Cycle (Proc. of an International Conference in Vienna, Austria, 15–19 June 2015), IAEA, Vienna (2019).	These proceedings present the outcome of the 2015 IAEA international conference on the management of spent fuel from nuclear power reactors. Achievements and lessons learned in connection with the back end of the nuclear fuel cycle and associated challenges were shared and reviewed.
INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Spent Fuel from Nuclear Power Reactors: Learning from the Past, Enabling the Future (Proc. of an International Conference in Vienna, Austria, 24–28 June 2019), Vienna (2020).	This publication presents the proceedings of the IAEA International Conference on the Management of Spent Fuel from Nuclear Power Reactors, held in 2019, with the theme ‘Learning from the Past, Enabling the Future’. The purpose of the event was to provide a forum for the exchange of information on national spent fuel management strategies and on the ways in which a changing energy mix could influence these strategies and on how they support the achievement of national energy goals. The broad scope of the conference covered all stages of the management of spent fuel from the past, present and future technologies, and how it can be affected by the decisions taken in the rest of the nuclear fuel cycle.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
	Cost
INTERNATIONAL ATOMIC ENERGY AGENCY, Cost Analysis Methodology of Spent Fuel Storage, Technical Reports Series No. 361, IAEA, Vienna (1994).	This report provides a methodology for calculating the costs of different options for interim storage of spent fuel produced in reactor cores. It considers different technical features and storage options and defines the factors affecting all options. The report further analyses the major cost categories, calculates the net present value of each option and determines the levelized cost. It also includes a sensitivity analysis, taking into account the uncertainty of the different cost estimates.
INTERNATIONAL ATOMIC ENERGY AGENCY, Costing of Spent Fuel Storage, Nuclear Energy Series NF-T-3.5, IAEA, Vienna (2009).	This publication provides guidance on the methods for estimating spent fuel storage costs. It includes basic cost input data breakdowns and cost analysis methods for project evaluation and comparison between options. Financial and business aspects of spent fuel storage are also discussed. Surveys of key software tools and example calculations are given in the annexes.
INTERNATIONAL ATOMIC ENERGY AGENCY, Costing Methods and Funding Schemes for Radioactive Waste Disposal Programmes, Nuclear Energy Series NW-T-1.25, IAEA, Vienna (2020).	This publication provides Member States with information on developing cost estimates for a disposal programme and establishing funding mechanisms. The publication is applicable to all waste categories and both near surface and geological disposal. It contains relevant examples and case studies from national programmes. The cost figures are intended to give an indication of the possible cost of certain parts or aspects of the disposal programme rather than to compare the costs of different disposal programmes.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
Damaged fuel	
INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Severely Damaged Nuclear Fuel and Related Waste, Technical Reports Series No. 321, IAEA, Vienna (1991).	This publication provides a comprehensive review of management insights and principles related to on-site, post-accident activities at NPPs experiencing significant fuel damage. It combines information on emergency response procedures and off-site plans with a discussion of on-site experience. It provides a reference text on the requirements that arise after the critical phase of emergency response.
INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Damaged Spent Nuclear Fuel, Nuclear Energy Series NF-T-3.6, IAEA, Vienna (2009).	This publication provides assistance in determining if fuel with a particular type of defect is acceptable or if it requires non-standard handling. The publication is intended to facilitate evaluation of the costs and benefits of design concepts or design changes for storage or transport systems and to help in selecting appropriate methods for identifying and handling damaged SNF.
Stakeholder involvement	
INTERNATIONAL ATOMIC ENERGY AGENCY, Stakeholder Involvement Throughout the Life Cycle of Nuclear Facilities, IAEA Nuclear Energy Series NG-T-1.4, IAEA, Vienna (2011).	While acknowledging the existence of different national approaches, this publication proposes a route to effective stakeholder involvement throughout the main phases of the life cycle of nuclear facilities (i.e. construction, operation, radioactive waste management, decommissioning) and the use of up-to-date methods to implement stakeholder involvement programmes. This publication demonstrates the importance of stakeholder involvement throughout the life cycle of nuclear facilities, including operating reactors, temporary spent fuel storage facilities and final radioactive waste repositories.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
Emergency preparedness	
INTERNATIONAL ATOMIC ENERGY AGENCY, Actions to Protect the Public in an Emergency due to Severe Conditions at a Light Water Reactor, EPR-NPP-PPA, IAEA, Vienna (2013).	This publication is part of the IAEA's Emergency Preparedness and Response (EPR) series. It provides the basic information and criteria needed by a decision maker in order to protect the public during an emergency involving severe fuel damage in a LWR or graphite moderated reactor (RBMK) core or spent fuel pool. This publication applies to reactors with power levels greater than 30 MW(e) (100 MW(th)) and to spent fuel pools that contain reactor fuel that needs to be actively cooled to prevent overheating and failure of the fuel. It takes account of the lessons learned from response to past emergencies, including the accident at TEPCO's Fukushima Daiichi Nuclear Power Station in 2011, and from latest research.
Safeguards	
INTERNATIONAL ATOMIC ENERGY AGENCY, International Safeguards in the Design of Facilities for Long Term Spent Fuel Management, IAEA Nuclear Energy Series NF-T-3.1, IAEA, Vienna (2018).	This publication provides guidance on the inclusion of safeguards in nuclear facility design and construction. It is principally intended for designers and operators of facilities for long term spent fuel management. It covers general as well as specific safeguards considerations related to transport, and wet and dry storage of spent fuel.
Decommissioning of storage facilities	
INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Nuclear Facilities Other Than Reactors, Technical Reports Series No. 386, IAEA, Vienna (1998).	This publication specifically addresses the decommissioning of non-reactor nuclear facilities. It applies in particular to the nuclear fuel cycle, including uranium conversion, enrichment and fuel fabrication facilities, reprocessing plants and waste or spent fuel storage and treatment facilities, but also includes analytical and research laboratories. It highlights distinctive factors in the decommissioning of non-reactor nuclear facilities as compared to those for reactors.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Pools in Nuclear Facilities, IAEA Nuclear Energy Series NW-T-2.6, IAEA, Vienna (2015).	A number of nuclear installations use pools to cool spent fuel or to shield research reactor cores or irradiation sources. Over a service lifetime that can span decades, nuclear pools may become contaminated as a result of the deposition of radioactive substances. Relevant aspects of pool decommissioning covered in this publicationinclude project planning and management, health and safety and the management of resulting waste.
Security (storage and transportation)	
INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Rev. 5), IAEA Nuclear Security Series No. 13, IAEA, Vienna (2011).	This publication provides guidance to States and their competent authorities on how to develop or enhance, implement and maintain a physical protection regime for nuclear material and nuclear facilities through the establishment or improvement of their capabilities to implement legislative and regulatory programmes. The recommendations presented in this publication reflect a broad consensus among IAEA Member States on the requirements which should be met for the physical protection of nuclear materials and nuclear facilities.
INTERNATIONAL ATOMIC ENERGY AGENCY, Physical Protection of Nuclear Material and Nuclear Facilities (Implementation of INFCIRC/225/Rev. 5), Nuclear Security Series Implementing Guide No. 27-G, IAEA, Vienna (2018).	This publication is the lead Implementing Guide in a suite of guidance on implementing the nuclear security recommendations on the physical protection of nuclear material and nuclear facilities. It provides guidance and suggestions to assist States and their competent authorities in establishing, strengthening and sustaining their national physical protection regime and implementing the associated systems and measures, including operators’ physical protection systems.
INTERNATIONAL ATOMIC ENERGY AGENCY, Establishing a System for Control of Nuclear Material for Nuclear Security Purposes at a Facility during Use, Storage and Movement, Nuclear Security Series No. 32-T, IAEA, Vienna (2019).	This publication focuses on the control of nuclear material during storage, use and movement using a facility’s nuclear material accounting and control system.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Security during the Lifetime of a Nuclear Facility, IAEA Nuclear Security Series No. 35-G, IAEA, Vienna (2019).	This publication provides guidance to States, competent authorities and operators on appropriate nuclear security measures during each stage in the lifetime of a nuclear facility, from initial planning of the facility through to its final decommissioning. The publication addresses effective nuclear security in the transition between stages and applies to the nuclear security of nuclear material and nuclear facilities throughout the lifetime of all types of nuclear facility.
INTERNATIONAL ATOMIC ENERGY AGENCY, Security of Radioactive Material in Transport, Nuclear Security Series No. 9-G (Rev. 1), IAEA, Vienna (2020).	This updated version of IAEA Nuclear Security Series No. 9, Security of Radioactive Material in Transport, is intended to facilitate the establishment of an internationally consistent approach to security of radioactive material in transport. It is applicable to the security of packages containing radioactive material that could cause unacceptable radiological consequences.
Burnup and MOX	
INTERNATIONAL ATOMIC ENERGY AGENCY, Implementation of Burnup Credit in Spent Fuel Management Systems, IAEA-TECDOC-1241, IAEA, Vienna (2001).	The publication explores the status of international activities related to the use of burnup credit for spent fuel applications. Burnup credit for wet and dry storage systems is needed in many Member States to allow for increased initial fuel enrichment, and to increase the storage capacity and thus to avoid the need for extensive modifications of the spent fuel management systems involved.
INTERNATIONAL ATOMIC ENERGY AGENCY, Practices and Developments in Spent Fuel Burnup Credit Applications, IAEA-TECDOC-1378, IAEA, Vienna (2003).	This publication documents the proceedings of the IAEA's third major burnup credit meeting in Madrid in April 2002 on requirements, practices and developments in burnup credit applications.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Status and Advances in MOX Fuel Technology, Technical Reports Series No. 415, IAEA, Vienna (2003).	This publication gives an overview of the worldwide state of plutonium fuel development. Information on the status of, and development trends in, MOX fuel technology in the areas of design, fabrication, performance, in-core fuel management, transportation, spent MOX fuel management, decommissioning, waste treatment, safeguards and alternative approaches for plutonium recycling is provided. The publication concentrates on MOX fuel for thermal power reactors.
INTERNATIONAL ATOMIC ENERGY AGENCY, Advances in Applications of Burnup Credit to Enhance Spent Fuel Transportation, Storage, Reprocessing and Disposition (Proc. of a Technical Meeting in London, 29 August–2 September 2005), IAEA-TECDOC-1547 (2007).	This publication records the proceedings of a technical meeting organized by the IAEA and held in London 29 August–2 September 2005 with 60 participants from 18 countries. As indicated in the title, the objective of this meeting was to provide a forum for exchange of technical information on spent fuel burnup credit applications and thereby compile state of the art information on technical advances related to spent fuel transportation, storage, reprocessing and disposition.
Spent Fuel Management	
INTERNATIONAL ATOMIC ENERGY AGENCY, Spent Fuel Surveillance and Monitoring Methods (Proc. of a Technical Committee Meeting, Vienna, 27–30 October 1987), IAEA-TECDOC-461, IAEA, Vienna (1988).	The publication contains the papers presented during the Technical Committee Meeting on Spent Fuel Surveillance and Monitoring Methods, held in Vienna, in October 1987. The papers included information on available designs and operation criteria, safety principles and licensing requirements and procedures in order to prevent: inadvertent criticality, undue radiation exposure and unacceptable release of radioactivity as well as control for loss of storage pool water, crud impact, water chemistry, distribution and behaviour of particulates in cooling water, oxidation of intact and failed fuel rods as a function of temperature and burnup, distribution of radiation and temperature through dry cask wall, monitoring of leakages from pools and gas escapes from dry storage facilities, periodic integrity tests of the containment barriers, and responsibilities of organizations for the required operation, structure, staff and subordination.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
International Atomic Energy Agency, Options, Experience and Trends in Spent Nuclear Fuel Management (1995), Technical Reports Series No. 378, IAEA, Vienna (1995).	The purpose of this publication is to assist Member States to establish policies and national arrangements for spent fuel management in a structured and timely manner. A dedicated chapter on storage technologies is included.
INTERNATIONAL ATOMIC ENERGY AGENCY, Remote Technology in Spent Fuel Management (Proc. of an Advisory Group Meeting, Vienna, 22–25 September 1997), IAEA-TECDOC-1061, IAEA, Vienna (1999).	The publication reviews remote technologies in use for the complete range of spent fuel handling and spent fuel management covering wet and dry environments, to describe ongoing developments.
INTERNATIONAL ATOMIC ENERGY AGENCY, Institutional Framework for Long Term Management of High Level Waste and/or Spent Nuclear Fuel, IAEA-TECDOC-1323, IAEA, Vienna (2002).	This publication provides a compilation of information on the institutional aspects of national programmes for long term management of HLW and spent fuel such as implementation, regulatory and oversight activities, definition of responsibilities, repository site selection processes, management costs and financing schemes.
INTERNATIONAL ATOMIC ENERGY AGENCY, Remote Technology Applications in Spent Fuel Management, IAEA-TECDOC-1433, IAEA, Vienna (2005).	This publication gives a review of the current status of remote technology applications for spent fuel management. The scope of the review covers the series of spent fuel handling operations involved in spent fuel management, from discharge from reactor to reprocessing or packaging for disposal, depending on the options chosen for spent fuel management. Because of the predominant amount of work required for spent fuel storage in the current and foreseeable future requirements for spent fuel management, more details are described on remote technology associated with storage of spent fuel.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Data Requirements and Maintenance of Records for Spent Fuel Management: A Review (2006), IAEA-TECDOC-1519, IAEA, Vienna (2006).	To allow informed decisions for spent fuel management to be made, the data need to be maintained throughout the lifetime of spent fuel management including storage, transport, reprocessing or disposal. This publication is intended to provide a state of the art review of spent fuel data management, including what data need to be gathered for the relevant activities in spent fuel management and how to maintain them by the responsible bodies at various stages of the nuclear fuel cycle.
INTERNATIONAL ATOMIC ENERGY AGENCY, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, IAEA International Law Series No. 1, IAEA, Vienna (2006).	This publication brings together in a more convenient format the official records and other relevant publications relating to the negotiations on the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. The Convention applies to spent fuel and radioactive waste resulting from civilian nuclear reactors and applications and to spent fuel and radioactive waste from military or defence programmes if and when such material is transferred permanently to and managed within exclusively civilian programmes, or when declared as spent fuel or radioactive waste for the purpose of the Convention.
INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Fuel Cycle Information System, IAEA-TECDOC-1613, IAEA, Vienna (2009).	The Nuclear Fuel Cycle Information System (NFCIS) is an international directory of civilian nuclear fuel cycle facilities, published online as part of the Integrated Nuclear Fuel Cycle Information System. This is the fourth hardcopy publication in almost 30 years, and it represents a snapshot of the NFCIS database at the end of 2008.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Impact of High Burnup Uranium Oxide and Mixed Uranium-Plutonium Oxide Water Reactor Fuel on Spent Fuel Management, Nuclear Energy Series NF-T-3.8, IAEA, Vienna (2011).	This publication examines the many aspects of the increased use of high burnup UOX and MOX fuel, and its potential impact on spent fuel management as well as on the whole nuclear industry. It discusses reactor types, with emphasis on LWR and HWR technology, considers the current state of UOX and MOX worldwide, provides information on the various fuel and cladding types and spent fuel management components and elaborates on the characteristics of spent fuel related to higher burnup UOX and MOX fuels, followed by a detailed analysis.
INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Fuel Cycle Objectives, IAEA Nuclear Energy Series NF-O, IAEA, Vienna (2013).	This publication establishes the criteria that need to be fulfilled in the area of the nuclear fuel cycles in order to satisfy the Nuclear Energy Basic Principles for resources, fuel engineering and performance, spent fuel management and reprocessing and research reactor nuclear fuel cycles.
INTERNATIONAL ATOMIC ENERGY AGENCY, Potential Interface Issues in Spent Fuel Management, IAEA-TECDOC-1774, IAEA, Vienna (2015).	Taking a holistic view of the nuclear fuel cycle ensures that influences from and effects on all phases of the nuclear fuel cycle are clearly understood. This general view facilitates effective decision making in the back end of the fuel cycle. Particular challenges include maintaining flexibility to accommodate the range of potential future spent fuel disposition options as well as defining and addressing the relevant issues in storage and transportation; given the uncertainties about the storage duration, the availability of future technologies and also of future financial, regulatory and political conditions. This publication provides an approach to identify the interfaces in the BEFC as well as the potential issues related to those interfaces that should be addressed. It also provides examples of Member States approaches on identifying and addressing interface issues.

TABLE 11. LIST OF IAEA PUBLICATIONS RELATED TO SPENT FUEL STORAGE (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Options for Management of Spent Fuel and Radioactive Waste for Countries Developing New Nuclear Power Programmes (Rev. 1), Nuclear Energy Series NW-T-1.24 (Rev. 1), IAEA, Vienna (2018)	This publication provides a concise summary of key issues related to the development of a sound radioactive waste and SNF management system. It is intended to brief countries with small or newly established nuclear power programmes about the challenges of, and describe current and potential alternatives for, managing reactor waste and spent fuel arising during the operation and decommissioning of NPPs.
INTERNATIONAL ATOMIC ENERGY AGENCY, Status and Trends in Spent Fuel and Radioactive Waste Management, Nuclear Energy Series NW-T-1.14, IAEA, Vienna (2018).	Based on the outcome of a collaborative project undertaken by the IAEA, NEA and the European Commission, this publication provides a global overview of the status of radioactive waste and spent fuel management concerning inventories, programmes, current practices, technologies and trends. It includes an analysis of national arrangements and programmes for radioactive waste and spent fuel management, an overview of current waste and spent fuel inventories and estimates of future amounts. International and national trends in these areas are also addressed.

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GLOSSARY

ageing management. Engineering, operations and maintenance actions to control within acceptable limits the ageing degradation of structures, systems and components.

Examples of engineering actions include design, qualification and failure analysis. Examples of operations actions include surveillance, carrying out operating procedures within specified limits and performing environmental measurements.

at reactor (AR) storage facility. A storage facility (pool) co-located with the reactor, inside the containment building.

away from reactor (AFR) storage facility. A wet or dry storage facility that is not co-located with the reactor, meaning that the fuel has to be transferred or transported to the storage facility. There are two classifications: **Reactor site (RS**) refers to a storage facility that is located within the reactor site boundary but is located independently from the reactor and requires spent fuel to be transferred from one facility to the other. A further distinction can be made for an AFR-RS in terms of those that stand alone and can still support operations if the reactor is decommissioned and those that are reliant on reactor services. **Off-site (OS)** refers to a storage facility that is located outside the reactor site boundary and that requires spent fuel transportation on public roads.

basket. A moveable feature holding a number of spent fuel assemblies.

burnup. A measure of reactor fuel consumption equal to the amount of energy released per unit mass of nuclear fuel in the reactor (for power reactor fuel). Typical units for the latter are megawatt-days per tonne (MWd/t) of uranium or gigawatt-days per tonne (GWd/t).

canister (can). A container (usually cylindrical) for remotely handled spent fuel or high level waste that affords physical containment and some shielding, but extra shielding may be required.

canisterized system. A storage system in which a number of fuel assemblies are placed into a canister, the contents dried and the canister welded closed for subsequent handling operations for storage and transport.

canned spent fuel. (mainly USA) Damaged fuel placed within a spent fuel can to permit its handing.

cask. A vessel for the transport and/or storage of spent fuel and other radioactive materials. The cask serves several functions. It provides chemical, mechanical, thermal and radiological protection, and dissipates decay heat during handling, transport and storage.

cladding, fuel. Typically, the tube of material that houses nuclear fuel pellets and provides the containment (means of containment) of radionuclides.

cladding defect. Through-wall penetration in fuel cladding caused by a manufacturing fault or by in-reactor service and/or post-irradiation handling and storage. It may lead to the release of radioactive material.

component. One of the parts that make up a system, including hardware (e.g. wires, transistors, integrated circuits, motors, relays, solenoids, pipes, fittings, pumps, tanks, valves) or software (e.g. modules, routines, programmes, software functions).

composite. Materials commonly used for neutron absorption. The two types in regular use are sandwich type, in which B_4C is sandwiched between two plates of aluminium, and the metal matrix composites, in which B_4C is dispersed within the metal matrix.

container. A general term for a receptacle designed to hold spent fuel to facilitate movement and storage or for eventual disposal.

corrosion, localized. Corrosion occurring at discrete sites on the surface of a material. For spent fuel in wet storage there are three theoretical mechanisms:
galvanic corrosion. In wet storage, the preferential attack of one of two electrically dissimilar metals which are in electrical contact if the pool water acts as an electrolyte. Galvanic corrosion is an area of potential concern for fuel assembly materials in contact with storage racks, containers, etc.
microbial induced corrosion (MIC). Corrosion resulting from the activity of microbes (i.e. growth of a biofilm and creation of a localized environment that is detrimental to the metal they cover).
pitting corrosion. Corrosion resulting from the localized depassivation of the metal's protective oxide layer due to attack by aggressive ions.

cost–benefit analysis. A systematic technical and economic evaluation of the positive effects (benefits) and negative effects (disbenefits, including monetary costs) of undertaking an action.

creep. An increase in the length or diameter of a material over time as a result of one or more applied stressors. As the material expands it will become thinner until a point is reached when it ruptures. For fuel cladding, the stressors are internal fuel rod pressure and cladding temperature. Creep is also a function of material composition and condition.

degradation, fuel. Changes in the condition of the fuel which may adversely affect the subsequent handling, storage and treatment of the fuel, for example, fuel pin bowing, cladding failure, pellet defect and loss of structural integrity.

delayed hydride cracking (DHC). A very specific mechanistic process requiring triaxial stressing of the zirconium to dilate the crystal lattice. Triaxial stresses dilate the zirconium lattice tetrahedral sites, which are the ones occupied by hydrogen atoms in solution. This allows the hydrogen atoms to diffuse up the stress gradient and precipitate in the peak stress region. Although DHC has been observed in Zircaloy specimens that are sufficiently thick, DHC is not expected to be an active degradation mechanism in cladding tubes, given that the latter do not appear to have enough wall thickness to generate much triaxial stress.

design basis accident (DBA). A postulated accident leading to accident conditions for which a facility is designed in accordance with established design criteria and conservative methodology, and for which releases of radioactive material are kept within acceptable limits.

design extension condition (DEC). Postulated accident conditions that are not considered for DBAs, but that are considered in the design process of the facility in accordance with best estimate methodology, and for which releases of radioactive material are kept within acceptable limits. For NPPs and research reactors, DECs comprise conditions in events without significant fuel degradation and conditions in events with melting of the reactor core.

dry storage. Storage in a gaseous medium, such as air or an inert gas. Dry storage facilities include facilities for the storage of spent fuel in casks, silos or vaults.

dual purpose cask (DPC). A cask used for both storage and off-site transportation.

ductile-to-brittle transition temperature (DBTT). The temperature at which there is a pronounced decrease in a material's ability to absorb force without fracturing. At this point, a material transitions from ductile to brittle.

embrittlement. A significant decrease in ductility of a material, which makes it brittle. Used to describe any phenomena where the environment compromises a stressed material's mechanical performance, such as temperature or environmental composition.

fatigue. A condition in which a particular material or structure has exceeded its projected life and becomes more likely to experience material failures.

fuel assembly. A set of fuel rods and associated components which are loaded into and subsequently removed from a reactor core as a single unit.

fuel element. A rod of nuclear fuel, its cladding and any associated components necessary to form a structural entity. Commonly referred to as a **fuel rod** in light water reactors.

fuel pellet. The manufactured form of ceramic nuclear fuels, mainly oxide, but also carbide and nitride formed by compaction and sintering of powder or fuel microspheres in the diameter range of 10–1000 μm.

fuel rod. A basic component of nuclear fuel fabricated for service in a reactor comprising fissile and/or fertile material (oxide or metal) sealed in a metal tube; also called *fuel pin* and *fuel subassembly*.

hydrogen migration and redistribution. The migration of hydrogen, in solid solution, from the high temperature region of the cladding to the low temperature region due to axial temperature profiles in the storage system. Hydrogen will precipitate in the colder regions in the form of hydrides, if and only if, a high enough supersaturation is realized. When this is the case, precipitation of hydrides leads to increased embrittlement, which may affect fuel integrity.

hydride reorientation. A process whereby precipitated zirconium hydrides dissolve into the solid metal matrix, up to the point of hydrogen saturation, and can reorient into a different direction during cooling under inner pressure of the rod. If the hydride reorients from the circumferential to radial direction, the mechanical properties of the fuel cladding can be impacted.

mixed oxide fuel (MOX fuel). Nuclear reactor fuel which contains more than one type of fissile nuclide, both or all being in the form of oxides. Most commonly refers to fuel containing both uranium oxide and plutonium oxide.

multipurpose cask, multipurpose canister (MPC). A cask or canister storage system planned to meet disposal requirements in addition to storage and transportation.

overpack. A secondary (or additional) outer container for one or more waste or spent fuel packages, used for handling, transport, storage and/or disposal.

package design safety report (PDSR). Document supporting an application for approval of the package design by the competent authority. This report provides the full description of the package design and the demonstrations of compliance with the regulatory requirements applicable to this package design.

reprocessing. A process or operation the purpose of which is to extract radioactive isotopes from spent fuel for further use.

ring compression test (RCT). A method used to determine the ductility of fuel cladding through the application of applied load using a controlled displacement rate.

safeguards. Technical measures through which IAEA seeks to independently verify a State’s legal obligation that nuclear facilities are not misused and nuclear material is not diverted from peaceful uses.

safety analysis. Evaluation of the potential hazards associated with the operation of a facility or the conduct of an activity.

The formal safety analysis is part of the overall safety assessment; that is, it is part of the systematic process that is carried out throughout the design process (and throughout the lifetime of the facility or the activity) to ensure that all the relevant safety requirements are met by the proposed (or actual) design.

Safety analysis is often used interchangeably with *safety assessment*. However, when the distinction is important, *safety analysis* should be used as a documented process for the study of safety, and *safety assessment* should be used as a documented process for the evaluation of safety — for example, evaluation of the magnitude of hazards, evaluation of the performance of safety measures and judgement of their adequacy, or quantification of the overall radiological impact or safety of a facility or activity.

safety standards. Standards issued pursuant to Article III(A)(6)[1] of the Statute of the IAEA.
Requirements, regulations, standards, rules, codes of practice or recommendations established to protect people and the environment against ionizing radiation and to minimize danger to life and property.
Safety standards issued since 1997 in the IAEA Safety Standards Series are designated as Safety Fundamentals, Safety Requirements or Safety Guides.
Some safety standards issued prior to 1997 in the (defunct) Safety Series were designated Safety Standards, Codes, Regulations or Rules.

silo. A fixed or movable structure comprising one or more individual storage cavities. The silo affords all safety functions of a storage facility (i.e. structural support and radiological protection).

spent fuel. 1. nuclear fuel removed from a reactor following irradiation that is no longer usable in its present form because of depletion of fissile material, poison buildup or radiation damage.
2. Nuclear fuel that has been irradiated in and permanently removed from a reactor core.

spent fuel management. All activities that relate to the handling (including reprocessing and recycling) or storage of spent fuel, excluding off-site transport.

spent fuel management facility. Any facility or installation the primary purpose of which is spent fuel management.

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[1] The Agency is authorized "to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property (including such standards for labour conditions)…".

spent fuel pool. Wet storage facility at or away from the NPP. The water in the pool surrounding the fuel provides heat dissipation and radiation shielding, and the racks or other devices ensure a geometrical configuration that maintains subcriticality.

spent fuel storage. The process of emplacement and retention of spent fuel in a safe and retrievable manner. This implies a facility affording adequate environmental and physical protection. Shielding, containment of radionuclides, criticality control, and decay heat dissipation need to be provided.

storage rack, fuel. A structure in a wet or dry storage facility that holds spent fuel assemblies or storage containers in a configuration to control criticality, allow heat removal and facilitate fuel handling.

stress corrosion cracking (SCC). Cracking induced from the combined influence of tensile stress and a corrosive environment. The required tensile stresses may be in the form of directly applied stresses or in the form of residual stresses. One of the most important forms of stress corrosion that concerns the nuclear industry is chloride stress corrosion — a type of intergranular corrosion that occurs in austenitic stainless steel under tensile stress in the presence of oxygen, chloride ions, and high temperature.

structures, systems, and components (SSCs). A general term encompassing all of the elements (items) of a facility or activity that contribute to protection and safety, except human factors. Human factors may be reflected insofar as ergonomics — the study of people's efficiency in their work setting — is an element in their design.

structure*. A passive element (e.g. buildings, vessels, shielding).

system*. A set of components which interact according to a design so as to perform a specific (active) function, in which an element of the system can be another system, called a subsystem. Examples are mechanical systems, electrical systems and instrumentation and control systems.

vault. An above- or below-ground reinforced concrete structure containing an array of storage cavities, each of which could contain one or more fuel units with shielding provided by the exterior of the structure. Heat removal is principally by forced or natural movement of gases over the exterior of the fuel unit or storage cavity. Heat rejection to the atmosphere is either direct or via a secondary cooling system.

wet storage. Storage in water. The universal mode of wet storage consists of storing **spent fuel assemblies** or spent fuel elements in pools of water, usually supported on racks or in baskets and/or in canisters (see **spent fuel pool** definition).

Note: Definitions marked with (*) are taken from the 2018 edition of the IAEA Safety Glossary.

ABBREVIATIONS

AFR	away from reactor
AFR-OS	away from reactor, off-site
AFR-RS	away from reactor, on the reactor site
ALARA	as low as reasonably achievable
AMP	ageing management programme
AR	at reactor
BWR	boiling water reactor
CANDU	Canada deuterium uranium [reactor]
CANSTOR	CANdu STORage
ChNPP	Chernobyl nuclear power plant
CSF	Centralized Storage Facility, Spain
DEC	design extension condition
DHC	delayed hydride cracking
DPC	dual purpose cask
HLW	high level waste
ISF-2	interim spent nuclear fuel dry storage facility, Ukraine
JAPC	Japan Atomic Power Company
KKG	Gösgen Nuclear Power Plant, Switzerland
KMP	key measurement point
KTA	Der Kerntechnische Ausschuss (Nuclear Safety Standards Commission), Germany
LWR	light water reactor
MACSTOR	Modular Air-Cooled STORage
MCC	Mining and Chemical Complex, Russian Federation
MIC	microbial induced corrosion
MOX	mixed oxide (fuel)
MPC	multipurpose canister
MVDS	modular vault dry store
NPP	nuclear power plant
NUHOMS	NUclear HOrizontal Modular Storage system by Orano
PDSR	package design safety report
PWR	pressurized water reactor
RBMK	high power channel type reactor
RFS	Recyclable-Fuel Storage Company, Japan
SOLAS	International Convention for the Safety of Life at Sea
SONGS	San Onofre Nuclear Power Plant, California, USA
SCC	stress corrosion cracking
SPAR	Spent Fuel Performance Assessment and Research

SSC	systems, structures and components
TEPCO	Tokyo Electric Power Company, Japan
UOX	uranium oxide
WWER	water-water energetic reactors; also known as VVER

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This publication is a new edition of Technical Reports Series No. 240, Guidebook on Spent Fuel Storage (1991). It aims to provide guidance on spent fuel storage options, describing the history and observed trends of spent fuel storage technologies, gathering operational experiences and lessons learned. The evolving aspects related to higher burnup and mixed oxide (MOX) spent fuel, and the extension of storage timeframes are detailed. It also includes information on the distribution of the current global inventory of spent fuel by storage systems, a description of (and terminology relating to) available spent fuel storage technologies and different storage facility locations.

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