INTERNATIONAL NUCLEAR WASTE MANAGEMENT CONCEPTS

RESEARCH ANALYSIS

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Introduction

Broadly speaking, waste management concepts depend on three factors: first, on waste types, such as high-level waste (HLW) and low- and intermediate-level waste (LILW); second, on waste properties like level of radioactivity heat generation or half-life; and finally on national conditions such as the availability of waste management facilities, potential storage conditions, or waste quantities.
The largest quantities of nuclear waste result from operating and dismantling of nuclear power plants. Spent fuel from power plants is generally managed separately because of the possibility of reprocessing and the recovery from plutonium and uranium as valuable materials. Here it is to be noted that reprocessing is not a waste management technology. Nevertheless, spent fuel and different waste types from reprocessing have finally to be disposed of. The following figure shows the different paths of radioactive waste from nuclear power plants using Germany as an example.

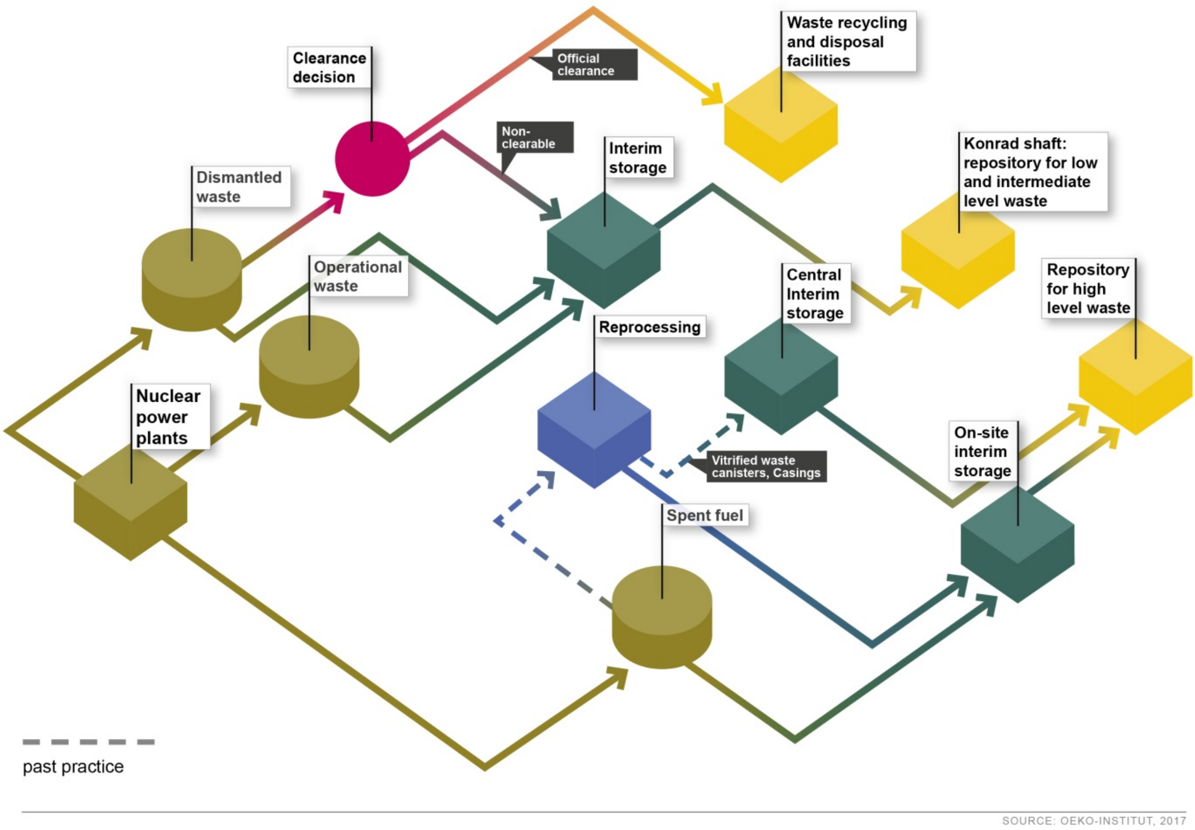

Figure 1: Example Germany: from nuclear power plant to repository, the paths of radioactive waste (source Öko-Institut e.V.)

Worldwide, the management of nuclear waste is governed by both national legislation and international conventions. Within the European Union (EU), the key framework is the Directive 2011/70/EURATOM for the responsible and safe management of spent fuel and radioactive waste. In 2015, EU member states had to submit national waste management concepts to the European Commission, similar to the reporting and review process under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (the „Joint Convention“).[1] Every three years thereafter, EU member states report on the implementation of Directive 2011/70.

By taking account of these reports, this chapter provides an overview of the range of waste management policies in different countries, with a focus on high-level waste (HLW) and low-and intermediate-level waste (LILW). In particular, the analysis will focus on storage and disposal by addressing the main nuclear waste streams. In addition to these, there are some more waste types with special challenges. Addressing them would go beyond the scope of this report, but for the sake of completeness are briefly touched upon here:

Legacy waste and "exotics"

Nuclear wastes started occurring with the beginning of the use of nuclear energy in the 1950s. Some wastes are very old, which causes different problems. Others are not well documented which means the inventory is not known completely. Waste products have corroded due to poor storage or processing conditions, or earlier processing conditions do not meet current requirements for storage or disposal. These so-called "exotics" are mostly small amounts compared to main waste paths but they need special handling which is not always clear at present. In addition, there may be more "exotics" which are not known today.

Plutonium and uranium from reprocessing, depleted uranium

Operators do not classify plutonium and uranium from reprocessing or depleted uranium from enrichment as waste because there are possibilities for further use, for example, in fuels or as a reserve for further enrichment. Therefore, they are not always named or quantified in official statistics and waste reports. Nevertheless, it is often unclear how to manage the amounts of these materials in the long term so that disposal is possible.

Radioactive waste from non-nuclear industry, medicine, research and education

Small amounts of radioactive waste result from use in industry, medicine and in research and education. Most countries offer possibilities to take over the waste management or especially for disused sealed sources there are contracts to give them back to the (abroad) producer company. These types of waste arise also in countries without nuclear facilities. For these countries, challenges could be to develop a management solution for the long term, and also to implement a regulatory system and to build up know-how and capacity for a regulatory body.

[1] The date of entry into force was 18 June 2001; for full text of the Joint Convention see https://www.iaea.org/sites/default/files/infcirc546.pdf

1 Management concepts for high level waste

1.1 Concepts and schedule

In almost every nuclear power plant, spent fuel pools were built at the same time as the reactor building. To reduce heat and radioactivity, spent fuels stay in these pools for about three to five years. The pool capacity is generally not designed to last the lifetime of the nuclear power plant, so the next step is storage as an interim measure in a wet or a dry storage facility (see next section). Planned storage time differs across countries and depends on the availability of a repository. At present, wet storage capacities are most commonly used worldwide. But many countries have decided to build additional dry storage capacities in the future. For example, Japan decided to strategically expand its dry storage.[2] The Recyclable Fuel Storage Center began operation in 2018. The decision was driven by the experience of the Fukushima accident in 2011, when the Tsunami washed over dry stored casks in horizontal position. The later opening and examination of the casks showed neither safety relevant changes in the seals nor in the inventory. Japan has also plans for further research about dry storage.[3]

Some countries reprocess spent fuel for recovering uranium and plutonium for further use (especially France and Japan, in the past Germany). This technology generates amounts of radioactive waste with different properties, such as a high radioactive fission product solution which has to be treated and packaged in a suitable way, in this example through vitrification. For these reasons, reprocessing is not considered to be a waste management procedure.

As a last step, it is necessary to isolate spent fuels and high-level waste from the accessible biosphere due to hazards from high activity over a very long time. A geological repository is as of today commonly considered to be the possibly safest option to dispose of spent fuels and high-level waste. To determine a site for a suitable repository for spent fuel and high-level waste remains challenging for every country. So far, no repository for high-level waste is in operation worldwide. The figure shows the plans for operation starts of deep geological repositories of the European member states. At present only Finland, Sweden and France have selected a repository site. Many disposal concepts have failed in the past. In practice, this leads to (very) long storage periods, intentional or unintentional.

[2] National Report of JAPAN for the Sixth Review Meeting, 2017, see http://www.nsr.go.jp/english/cooperation/conventions/JC.html

[3] National Report of JAPAN for the Sixth Review Meeting, 2017, see above

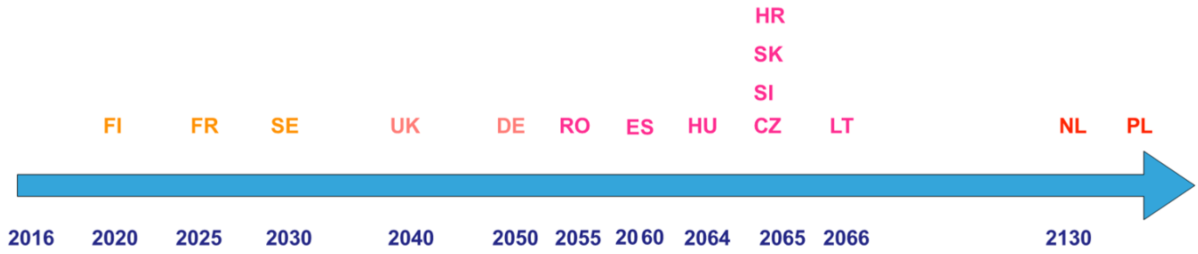

Figure 2 Planned start of operation of deep geological facilities in the European Union; the plans are more or less concrete (source[4])

In most countries, the responsibility for the waste management is assigned to the state. The following country examples show different approaches on waste management and schedules:

- The United States (US) initially saw an increasing need for dry storage capacities to bridge the gap until the Yucca Mountain repository was ready for operation. With the looming failure of the repository project, the desired storage periods became longer. In 2010, the supervisory authority developed its policies to ensure that spent fuel elements can be safely stored for up to 60 years after the end of a reactor's operating life. As the aim for reactor operation (including possible extensions) is 60 years, this means an interim storage period of 120 years.[5] However, the actual time requirement is completely open after the failure of the only repository option. There is neither an alternative nor strategies for finding a site at present.
- In the Netherlands a storage period of at least 100 years is planned for all types of radioactive wastes from two nuclear power plants and two research reactors. During this time, a geological repository for all waste types should be prepared “financially, technically and socially” to begin operation around 2130.[6] The final decision should be taken around 2100, when possible waste management alternatives should also be considered. An international collaboration to create a joint repository is being pursued in parallel.
- Germany has limited storage time for spent fuel and high-level waste storages to 40 years, this means until 2047 at the latest. But it is unlikely that a repository will be available by then. A site selection process has been started in 2017 with the aim of determining a disposal site by 2050. Experts consider this schedule as very ambitious and hardly manageable.[7] So extending the storage will be necessary and solutions are needed for

[4] Report from the commission on the council and the European parliament on progress of implementation of Council Directive 2011/70/EURATOM and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects, COM(2017) 236 final, 2017
[5] See 10 CFR 51.23, Continued Storage of Spent Nuclear Fuel, adopted 2014
[6] Netherlands: Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, National Report of the Kingdom of the Netherlands for the Sixth Review Meeting, The Hague, October 2017
[7] E. g. the Nuclear Waste Management Commission (ESK), see (translation) http://www.entsorgungskommission.de/sites/default/files/reports/eskdiskussionspapiervzl29102015homepageen.pdf

questions like: Which safety requirements for storage are needed? How long is the high level waste safely manageable? Which infrastructure is needed in the long term? And how or how long should know-how to be preserved?

- Finland is the first country that has granted a construction license for a final repository for spent fuel.[8] The license to build a KBS-3V repository was granted by the Radiation and Nuclear Safety Authority (STUK) and the Finnish government in 2015. The construction started in 2016. Finland's government set the long-term schedule for nuclear waste management, including site selection, already in 1983. At first, the public mood was against a repository, but this changed over time. In 2000, the competent municipal parliament voted for the site. However, the repository site was selected at a location where nuclear facilities were already located, close to the Olkiluoto nuclear power plant. The repository is approved for spent fuel from the five existing nuclear power plants in Finland, and is scheduled to begin operation in the early 2020s.
- Not all countries have defined their waste management strategies. For example, Italy which shut down its nuclear power plants after the Chernobyl accident, reprocessed about 30 t HM spent fuel abroad. The high-level waste will be expected back in 2025. For the time after there are no specific plans for storage. Plans for a geological disposal are not yet considered.[9]

One insight from delayed and failed disposal projects concerns the consideration of the public. Experiences suggest that the selection process for a repository site cannot be based solely on scientific and technical criteria. It is also necessary that the process is accepted by the public as comprehensible and fair. Accordingly, public participation in the site selection process plays an important role. Some countries try taking account of this. For example, the Swiss selection procedure and the new German selection procedure have laid down clear rules for public involvement in law. On the one hand this is an achievement in terms of accountability and public participation compared to the past. On the other hand some rules are still disputed, like …

1.2 Storage

With increasing operation time of nuclear power plants, the need for interim storage capacities for spent fuel elements has been steadily growing. In the EU, over 54,000 t HM spent fuel was stored by the end of 2013.[10] Storage capacities have therefore

[8] Finland: Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management 6th Finnish National Report as referred to in Article 32 of the Convention, October 2017, see http://www.julkari.fi/handle/10024/135375

[9] Implementation of Council Directive 2011/70/EURATOM of 19 July 2011, Establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, First Italian National Report, 2015, see http://www.enerwebwatch.eu/directive-euratom_2011-70-t46.html?langnav=en

[10] Report from the commission on the council and the European parliament on progress of implementation of Council Directive 2011/70/EURATOM and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects, COM(2017) 236 final, 2017

been expanded over time. Newly built storage facilities can be located at the nuclear power plant sites or off site at an independent location. This applies to wet and dry storage facilities.[11]

Wet Storage

Spent fuel pools are common to nuclear power plants in order to provide cooling following discharge from the reactor. In principle, long experience exists for the wet storage technology. Off-site wet storage facilities are often located at reprocessing plants, such as in France, the UK, Sweden, or Russia. The facilities consist of one or more pools for underwater storage of the spent fuels in storage racks. The pool fluid ensures heat removal and shielding. Subcriticality has to be maintained by spacing and/or neutron absorbing materials. In addition, they need systems for cask reception, decontamination, unloading, and maintenance. Facilities for water cooling and purification with continuous power supply are necessary. Furthermore radioactive waste handling (from water purification), radiation and water chemistry monitoring, leakage monitoring and other auxiliary systems are used.[12]

Dry Storage

Dry storage facility types for single purpose (only storage) are vaults or non-transportable casks. Over time, dual purpose casks (for transport and storage) have been developed, such as the CASTOR cask in Germany, TN 24 in Belgium and the NAC-STC in the US. Today there are many different cask types in use.

Vaults are modular reinforced concrete buildings with storage cavities for spent fuel.[13] They can be sited above or below ground. For storage, spent fuel has to be removed from a transportation cask and placed into a metal tube or cylinder which is later sealed. Other vaults systems contain already sealed canisters including spent fuel. Systems for canister or fuel handling are necessary. In case of active ventilation, components and systems are also needed. Vaults systems are used in Canada (ANSTOR/MACSTOR), Hungary (MVDS facilities at Paks), United Kingdom (Wylfa facility) and in the Netherlands (HABOG).

There are also dry storage facilities with one or double purpose casks in different types.[14] In general, these casks are single and sealed systems. They provide a metal body with baskets or a concrete body with a metal liner or canister inside. They are closed with welded or sealed lids. The loading and unloading of double purpose casks takes place at the nuclear power plant. In the other case, transfer casks are used for transport to the storage site. Metal casks with double purpose are used in Switzerland (ZWILAG) and Germany (Gorleben, Ahaus and others), while concrete casks are used especially in the US.

Since no fluid is used in dry storage facilities, shielding and heat removal must be ensured with other technical solutions. Shielding is achieved by the building

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[11] An overview and pictures give "Lessons learned from a review of international approaches to spent fuel management", 2016, see https://www.epj-n.org/articles/epjn/pdf/2016/01/epjn150078.pdf

[12] International Atomic Energy Agency (IAEA): Survey of wet and dry spent fuel storage, 1999, IAEA Tecdoc 1100

[13] International Atomic Energy Agency (IAEA): Storage of Spent Nuclear Fuel, 2012, No. SSG-15

[14] International Atomic Energy Agency (IAEA): Storage of Spent Nuclear Fuel, 2012, No. SSG-15

structure (vaults) or the cask body with barriers integrated and the lids system (casks). Heat removal is performed by forced or natural convection over the exterior of the cavities or the casks. Dry storage facilities also need systems and services for radiation protection, decontamination, and leak tightness monitoring.

Advantages and Disadvantages

Wet and dry storage both have advantages and disadvantages. The biggest advantage of dry storage is that safety is mainly based on passive components, so that a loss of power supply can result in failing monitoring systems but it has no effect on containment and shielding. This is the biggest disadvantage of wet storage, as it needs active components like pumps and power supply for cooling and water covering for shielding. A loss of power supply could result in loss of pool water, which can cause serious damages on spent fuel cladding until release.
An advantage of wet storage is a more effective heat removal with low thermal impacts on cladding material as a consequence. Because the pools can be viewed, surveillance is much easier and defects can be discovered soon. In order to inspect fuel assemblies during dry storage, it is necessary to open the cask or canister. That is very challenging and only possible in a nuclear power plant or a hot cell facility. The International Atomic Energy Agency (IAEA) requires in their General Safety Requirements the preference of passive systems, in particular for taking into account the expected period of storage.[15]

Extended Storage

Due to the lack of disposal facilities, storage periods will be extended worldwide. Thus the integrity and retrievability of spent fuel over the storage period is a growing challenge. The goal is to keep options open for further waste management paths and their requirements such as transport, conditioning, and packaging. In consequence, there is a great need for research, for example on the long-term behavior of fuel and degradation mechanisms, and also about data gaps for these topics. The international subcommittee of the EPRI Extended Storage Collaboration Program (ESCP) identifies i.a. technical data gaps for dry storage facilities especially by degradation mechanisms of cladding and welded canisters.[16] The report also shows that different countries have different problems depending on their specific dry storage system and the respective situation. Also the IAEA conducted different research programs to support international exchange of experience.[17]
Other topics concerning spent fuel management in the long-term are data provision and documentation, the handling of damaged spent fuel, and the influence of burnup and fuel type (uranium or MOX) of spent fuel.

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[15] IAEA: Predisposal Management of Radioactive Waste, Standards for General Safety Requirements Part 5 (No. GSR Part 5), 2009
[16] Electric Power Research Institute (EPRI): Extended Storage Collaboration Program, International Subcom-mittee Report, International Perspectives on Technical Data Gaps Associated With Extended Storage and Transportation of Used Nuclear Fuel, 2012
[17] Examples: IAEA Tecdoc 1293, Tecdoc 1343, Tecdoc 1680

1.3 Disposal

The countries in Europe in general aim for geological disposal of high-level radioactive waste. The same applies to most of the non-European countries using nuclear power, such as the United States, Canada, or the Russian Federation. Most of the countries with a nuclear program restrict the disposal of their nuclear waste to a site within their own territory.

A deep geological repository is an underground facility, such as a mine, that is constructed to take up hazardous or, in a narrower sense, radioactive waste. The IAEA defines a geological repository as a "facility for radioactive waste disposal located underground (usually several hundred metres or more below the surface) in a stable geological formation to provide long term isolation of radionuclides from the biosphere."[18] Because the intention of mining usually is to extract raw materials from sub-surface deposits (such as gold, or coal), the shafts and galleries of mines are made to last no longer than they are needed for the mining operation. Mines usually are not backfilled and sealed after operation, but flooded and left alone.

Barrier Concept

The idea of constructing a deep geologic repository is to ensure that the waste is kept away from the biosphere (groundwater, plants, animals and people), for a long period of time. Most national disposal programs require the repositories to be safe for periods from 100,000 up to 1,000,000 years. The goal of preventing migration of the waste or single nuclides from its underground repository to the biosphere shall be achieved by using a system of interacting barriers (also known as the multiple barrier concept).

One barrier could be the waste form itself, in that it has to be deposited in a form that is mechanically and chemically stable and not easily soluble. Another barrier is the disposal canister. Depending on the respective national concept, it is constructed to last as long as stability and tightness are required. The disposal chambers have to be backfilled and sealed tightly. The same applies to the shafts of the mine. The last barrier is the host rock itself. Each disposal concept has to take into account the interaction of the different barriers to provide a safe repository for the long periods of time foreseen. The different countries have different emphases, some focus mainly on the host rock, others on technical barriers.

Host Rocks

The international discussion mainly focuses on three types of rock to construct a deep geological repository for high-level radioactive waste. These are rock salt, clay, and crystalline rocks. Talking about clay one has to distinguish between clay, which means ductile, non-solid material and claystone, solidified clay that reacts brittle on mechanical stress. Crystalline rock is a generic term covering a broad range of rocks of crystalline genesis (in the context of waste management, usually granite is intended).

[18] IAEA: Safety Glossary. Terminology Used In Nuclear Safety and Radiation Protection. 2007 Edition. Page 167.

Rock salt is gas-tight and will provide a safe barrier against release of radioactive material. On the other hand, rock salt is soluble, but in a deep geological environment only over very long periods of time. It reacts ductile on mechanical stress and increased temperature in a repository, and will enclose the waste after closure of the mine. On the other hand, the orogenic pressure will destroy the waste canisters while enclosing them, there will be a timely limited barrier function of the canister. Crystalline rocks considered for constructing radioactive waste repositories in are mechanically stable, but usually contain fractures that provide paths for groundwater circulation. The barrier function against solution and migration of the waste has to be provided mainly by the canister and a backfilling of clay material, usually bentonite, surrounding each canister in a crystalline rock repository concept. On the other hand, this clay material is sensitive to high temperatures. It is meant to swell and enclose the waste canister in a water tight layer, so the temperature of the waste emplaced has to be limited. The same applies to disposal concepts in clay and claystone.

The decision on a host rock for a national repository mostly depends on the geologic properties of the national territory. In Europe, Belgium and France are investigating a repository concept in clay. Switzerland does as well, after abandoning a disposal concept in crystalline rocks. Sweden and Finland aim at disposing of their national nuclear waste in crystalline rocks, as there are no alternative host rocks situated within their national territories. The Czech Republic is looking for a site for a deep geological repository in granite within its territory. Germany has focused on a salt rock repository for many years; however, following the site selection law of 2017, all suitable types of host rocks are being investigated.

Reversibility, Monitoring and Retrievability

Additionally, there are disposal concepts that include reversibility, monitoring, and even retrievability of waste:

- Reversibility is a concept that aims at enabling a certain adaptability of disposal concepts. A reversible site selection process is organized in a line of steps and phases, structured by stops, milestones and decision points, which allow adapting or even reversing the process if necessary.
- Monitoring of the waste means surveillance of its physical and chemical properties. This challenge requires sensors that can withstand the environmental conditions inside a closed repository for a long period of time, an energy source to power them, and a way of sending signals from a backfilled disposal mine to the surface.
- Retrievability means that construction measures have to be taken to enable a withdrawal of the waste to the surface for some period of time following the waste emplacement. There are a number of reasons for retrievable waste emplacement. The most important is the chance to correct mistakes that may be made during waste disposal or to act in case of a malfunction inside the repository. A disadvantage may be that compromises are made at the expense of safety in order to enable or simplify retrieval.

There are different examples for considering monitoring, retrievability, and reversibility in national waste management concepts. For example, Canada considers post-closure monitoring, but many countries have not planned this aspect. In Germany, reversibility is part of the site selection process. The German disposal concept considers also retrievability during repository operation, and measures to facilitate recovery of the emplaced waste after closure are foreseen. The French operator ANDRA looked into the matter of reversibility of disposal steps and retrievability of emplaced waste from a repository.[19]

Examples of Site Selection

The progress of the national waste management programs varies from conceptual planning of disposal options up to the construction of a disposal facility. In Europe, the Netherlands, the UK, Germany, Belgium, Spain, Italy, the Czech Republic, Slovakia, Croatia, and Slovenia are the countries that have not selected a disposal site so far. Of these, the Netherlands, Slovakia, Croatia, and Slovenia explicitly approve of the idea of building a joint international repository. The Netherlands follows a national and an international repository concept as a dual strategy. Also Slovakia is following a two-way-strategy. Whilst in favor of an international repository on one hand, on the other hand Slovakia is actively working on a siting process for a national repository.

Croatia and Slovenia are a special case in that they are working on a joint nuclear power plant. The facility of Krško was built in the former state of Socialist Federal Republic of Yugoslavia and went into operation in 1983. After the breakup of Yugoslavia in 1992, Croatia and Slovenia co-operatively proceeded with the operation of Krško. This leads to the problem that there is no single country responsible for the management of the high-level waste from Krško, and therefore no national territory specified for the site of a disposal facility.

The UK, Germany, and the Czech Republic all had to face an interruption of their national disposal programs due to different kinds of public resistance. The same can be said about Switzerland, where the proposed disposal site at the Wellenberg had to be given up, followed by a reboot of the national siting process. In Germany, a new site selection law is in place since 2017. The national institutions have been reorganized, a more strict separation between operator and regulator has been installed, and a national site selection process is under way, starting from a blank national map.

In Belgium, an underground research laboratory is operated for the preparation of the siting for and construction of a national repository. In Slovakia, two sites have been selected for further examination. Switzerland is following a three-stage site selection process, called the "Sachplan geologische Tiefenlager"[20] that just entered a new phase. Three possible site regions will be investigated in depth from now on.

In Sweden and France, sites for the construction of a deep geologic repository have been selected. In the run-up to the site selection, Switzerland, France and Sweden all

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[19] ANDRA, "Position Paper on Reversibility", January 2016, see https://www.andra.fr/download/andra-international-en/document/577va.pdf

[20] Overview about site selection process in Switzerland and documents: https://www.ensi.ch/en/waste-disposal/deep-geological-repository/sectoral-plan-for-deep-geological-repositories-sgt/

drove up underground research laboratories still being in operation. In France, the Operator ANDRA is working on submitting a license application in 2019. The Swedish waste management process came to a temporary halt in 2007 when concerns of copper corrosion came up. The license application for the construction of the repository has been submitted by the Swedish operator SKB in 2011. All necessary pronouncements by the national institutions concerned in the case have been submitted to the government and SKB is waiting for a government decision on permissibility.
Finland is the only country in Europe in which a repository is already under construction. Based on the Swedish KBS-3-system, the repository is being built on the island of Olkiluoto.
In the US, the national repository project at Yucca Mountain was been stopped by the federal government in 2009. A new waste management option or disposal site has not been named so far.
Canada has followed a waste management concept called Adaptive Phased Management (APM) since 2007. The characteristics of APM are the phased management process with the opportunity to make adjustments at the end of each phase, and a monitoring concept to last even after closure of the repository. These aspects have in a similar way been taken up into the German site selection law.

2 Management concepts for low and intermediate level wastes

2.1 Concepts and schedule

Low- and intermediate-level waste arises during operation and dismantling of nuclear facilities. Waste types are very diverse: there are residues from water purification like ion exchange resins and evaporation residues, air filters, tools, or exchanged components and demolition waste. Radioactive waste is collected and sorted by activity and by type of waste. The next step is conditioning, the treatment of the waste that leads to stabilization and volume reduction. In most cases, waste is dried and pressed, cemented, incinerated or melted, and then packaged. Only solid or solidified waste will be disposed of. The containers must meet special requirements with regard to stability and tightness. The acceptance criteria of the repository or the storage facility are decisive as far as a repository exists or is designed. The next steps are disposal or storage of the waste.
The waste management steps mentioned are not necessarily carried out in time for the waste generation. Waste is also initially stored in its raw state or in a partially treated state. In Germany, for example, the repository Konrad is under construction, waste acceptance criteria are available and a product control for waste products is implemented. At the end of 2016, however, only 2.4 percent of the waste generated was conditioned and packaged for final disposal. Most of the waste is stored in intermediate stages. In addition, there is the waste that has not yet been treated or only pre-treated.

While high-level waste shall be disposed of worldwide in a geological repository, the disposal of low-level and intermediate-level radioactive waste follows different concepts. The waste properties have a major influence on this, as do the activity and often the differentiation in short-lived and long-lived waste. In addition, the (potential) availability of disposal facilities and their acceptance criteria determine the disposal concept of a country.

In Germany, for example, heat input is to be limited for the Konrad geological repository, a former iron ore mine with a clay barrier. This led to the classification into heat-generating waste and waste with negligible heat generation. In addition, all waste that cannot be disposed of in the Konrad repository due to heat generation or other boundary conditions must be disposed of in another disposal facility.
The commissioning of the Konrad repository has been postponed several times, most recently from 2022 to 2027.[21] As a consequence, and in conjunction with nuclear power plant dismantling, the demand for interim storage capacities at the nuclear facility sites is increasing. Also in Switzerland, the planned commissioning date was postponed several times and is now set for 2050. Here the low- and intermediate-level waste (LILW) repository is selected by a site selection process combined with the site selection for the high-level waste (HLW) repository.
France envisages near-surface repositories for LILW with short half-lives of less than 30 years. One such repository is in operation, another one is already closed. There is currently no repository for long-lived low-level waste. Long-lived intermediate-level waste is to be disposed of together with HLW.
A remarkable aspect in France is that very low-level radioactive waste from nuclear power plants is disposed of in its own near-surface repository, which is not subject to French nuclear supervision. In most other countries, a release practice is common in which a decision is made on the basis of thresholds as to whether the waste can be recycled, must be disposed of conventionally (in a landfill), or if it must be disposed of as radioactive waste.
For low-level waste (LLW) in Italy, criteria have been defined for the site selection for a near-surface-repository. A map identifying potential siting regions exists. Voluntarism of host communities is preferred, otherwise negotiations with regional authorities will have to be undertaken. Italy also plans to site a new national repository for LLW and ILW disposal and a long term storage facility for ILW and HLW.
The directive 2011/70/Euratom requires all EU member states to develop waste management concepts, even those without nuclear power plant programs. Countries that did not pass a final disposal policy or strategy by now include Portugal and Austria. Serbia, which aims for EU membership, has drafted a national radioactive waste management programs, but it is not in conformity with the directive.

2.2 Storage

Low- and intermediate-level waste (LILW) is stored after generation, between the steps of treatment and packaging and before disposal. Storage takes place in appropriate facilities on-site or off-site from the nuclear power plant, but also in the power plant itself as raw or pretreated waste.

[21] Press release Nr. 01/18 - Fertigstellung des Endlagers Konrad verzögert sich, see https://www.bge.de/de/pressemitteilungen/2018/03/pm-0118-fertigstellung-des-endlagers-konrad-verzoegert-sich/

Some countries operate central storage facilities. The Netherland has the COVRA storage facility for all kinds of radioactive waste. Germany also has central storage facilities in Gorleben and in Mitterteich, but there are storage facilities for operation and dismantling waste at the power plant sites as well. Switzerland also operates storage facilities on the respective nuclear power plant sites.
In contrast to HLW, there is in general no need for certain storage time after decay. An exception is the targeted decay storage for short-lived LLW which is released from waste management by means of a release process.
Safety requirements of storage facilities shall ensure an optimized radiation protection of workers and the public.[22] Potential incidents shall be considered. The storage management should be organized in such a way that waste package inspections and retrievability for reworking or for next waste management steps are possible. Furthermore, storage conditions shall not complicate the following waste management steps. For example, moisture in the room or the waste, poor ventilation, or unsuitable waste packages can cause corroding waste or waste packages. However, there are a lot of examples for corrosion. The consequence is a more or less complex new treatment and packaging for further storage, but also for transport and disposal.

In the past, bitumination was a common way of treating liquid waste in France. The bituminized ILW-LL shall be disposed of into the planned HLW repository. The expected heat generation from HLW leads to problems with the disposal of bituminzed LILW, as bitumen is flammable and radionuclides may be released from it. In storage facilities a fire incident can be a risk. So the French regulator Autorité de Sûreté Nucléaire (ASN) has recently been advising the operator, the Agence National pour la gestion de Déchets Radioactifs (Andra), to look into and provide a solution for these questions.[23]
The respective country sets the regulations and requirements for storing conditions and storage facilities. In addition, the storage facility itself defines storage acceptance criteria for waste form, properties, and the containers.

2.3 Disposal

Worldwide, there is a range of disposal options for very LLW and LILW which are in consideration or even in use. Because of the different waste management concepts and classification systems, it is challenging to compare solutions and progress of different countries directly. However, this section provides an overview.
The IAEA describes disposal as an emplacement with no retrieving intention (which does not mean retrieving is not possible). In the Safety Requirements SSR- 5[24] the IAEA differs for radioactive waste in between:

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[22] An overview about recommendations for storage facilities gives IAEA Safety Guide No. WS-G-6.1 "Storage of Radioactive Waste", 2006
[23] see for example: ASN, Avis n° 2018-AV-0300 de l'Autorité de sûreté nucléaire du 11 janvier 2018 relatif au dossier d'options de sûreté présenté par l'Andra pour le projet Cigéo de stockage de déchets radioactifs en couche géologique profonde, 11 January 2018
[24] IAEA: "Disposal of Radioactive Waste", Specific Safety Requirements No. SSR-5, 2011

- Specific landfill disposal - similar to conventional landfill for very low-level waste (VLLW), for example from dismantling.
- Near surface disposal - in engineered trenches or vaults on the ground or tens of meters below ground level for low level waste (LLW).
- Below ground facilities - consisting of constructed caverns / vaults or built of mines in tens of meters up to hundreds of meters below ground for intermediate level waste (ILW).
- Geological disposal- as described above mainly for high level waste (HLW) and spent fuel.
- Borehole disposal - a few hundred meters up to a few kilometers deep for small amounts of waste e.g. disused sealed sources (not been adopted by any state).

In this categorization, the IAEA assigns certain waste classes to certain disposal facility types (graded approach). Based on the respective hazard potential of the waste, the chosen disposal system must have the property of safely enclosing the waste for protecting people and the environment. The decision about the facility system lies at the respective country. Most countries have at least disposal concepts, and many have disposal facilities under construction or in use.

In France very low level waste (VLLW) is dumped into landfills which are constructed like trenches at the Centre industriel de regroupement, d'entreposage et de stockage (CIRES). After disposal, the trenches are filled up and planted. In the future, CIRES will have to be expanded due to the high amount of waste, or another disposal facility has to be built. Spain also disposes of VLLW into two disposal cells with the capacity for approximately 69,000 m³ at its facility El Cabril. In future, the capacity should be nearly doubled. In Sweden, VLLW from nuclear power plant operation is disposed of in near-surface-repositories at the nuclear power plants sites.

The Spanish facility El Cabril contains a disposal site also for LILW, which is placed in concrete casks that are later filled with mortar and then transferred into disposal vaults.[25] When the vault is full, it will be sealed and covered with various drainage and waterproof layers. A monitoring phase for about 300 years starts after closure. At Centre de l'Aube in France, LILW is disposed of in concrete bunkers in a near surface repository. An older facility for the same waste type, the Centre de la Manche, has already been closed.

A LLW repository in Cumbria, UK, originally constructed in the form of landfill-style trenches, has been remediated. The waste is now grouted in metal containers in concrete vaults.[26] An additional LLW repository is in Dounreay, Scotland, in operation. For intermediate level waste (ILW), the preferred strategy in England and Wales is geological disposal without the intention of retrieval; in Scotland, near surface disposal is the option. However, currently there is no disposal site for ILW in operation in the UK.

Germany and Switzerland decided to dispose of radioactive waste with negligible heat generation (Germany) or LILW (Switzerland) in a geological repository, too. In

[25] see http://www.enresa.es/eng/index/activities-and-projects/el-cabril, accessed 06 March 2019
[26] http://ukinventory.nda.gov.uk/about-radioactive-waste/how-do-we-manage-radioactive-waste/, accessed 01 March 2019.

Germany, however, the repository does not use the old mine workings of the former iron ore mine but builds new galleries and storage chambers for the repository. In Switzerland, the repository will be constructed by mining after site selection process. Similar to Germany, the Czech Republic is using abandoned mines for the disposal of LILW, but in shallow depth only. The former limestone mine Richard with a depth of 70-90 meters below surface has been refurbished for disposal of institutional waste. LILW from the nuclear power plants at Temelin and Dukovany is disposed of in a surface repository at the Dukovany site. The Hostim Repository with a volume of around 1690 m^3 in an abandoned limestone mine was permanently sealed in 1997. Similar to HLW, Slovenia and Croatia have no disposal facility for LILW nuclear waste, mainly originating from the nuclear power plant at Krško operated by the two countries. A bilateral treaty on nuclear waste disposal exists. Apart from that, a disposal site for short lived LILW is to be built in Vrbina, Slovenia. Waste shall be disposed of in concrete silos in a plant of a modular, expandable design.
The Netherlands cannot use the strategy of near surface disposal of LILW, because all over the national territory the groundwater level is very close to the surface. Therefore, geological disposal is the option for all Dutch waste that cannot be released.
At the moment, Luxembourg is the only European country that uses an international agreement for waste management: all national radioactive waste is shipped to Belgium, where it is disposed of.

3 Discussed Alternatives

Alternatives to final disposal are being discussed due to many examples of failed repository projects worldwide and the predominantly low acceptance of a repository in one's own neighborhood. Even outer space is discussed as a suitable disposal site. This idea does not play a role among experts, due to the technical and financial effort involved and the risk of accidents such as explosion in the initial phase. Similarly, disposal in the sea or the seabed is now excluded by international treaties.

It is a common understanding that every waste management solution, whether geological disposal or alternatives, must protect the population and the environment in the best possible way, be feasible and tolerated, and not impose unreasonable burdens on future generations. Article 11 of the "Joint Convention" describes this understanding as follows: "Each Contracting Party shall take the appropriate steps to ensure that at all stages of radioactive waste management individuals, society and the environment are adequately protected against radiological and other hazards."[27]
Final disposal in deep boreholes is discussed as a possible alternative to geological disposal in a mine.[28] Therefore, high-level radioactive waste casks are to be dumped in boreholes up to 5,000 meters deep where several casks can be stacked on top of each other. The great depth and the many different overlapping barrier-effective layers are regarded as advantages. In addition, the host rock is less disturbed by a borehole than in a mine. However, with such a concept, it is much more difficult to

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[27] The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management
[28] Endlagerkommission Abschlussbericht

implement a retrieval or recovery operation. Open points include cask stability (ballast), backfilling fluid and closures, as well as sufficiently large borehole diameters at great depths. Since only mud drilling methods can be considered for these depths and the borehole must be filled with a fluid for stabilization, the waste package is also stored in this fluid. This has consequences for corrosion and gas generation, which also still have to be researched. So far, deep boreholes have been discussed mainly in the USA.[29] However, planned pilot tests were not continued due to other priorities.[30]

The so-called partitioning and transmutation (P+T), in which individual radionuclides are separated from the waste and converted into nuclides with a shorter half-life by neutron irradiation, is being investigated. The idea is to reduce the risk potential in this way. So far, despite many years of research, proof of feasibility has only been achieved for a few nuclides on a laboratory scale. This means that a repository with the same high safety requirements as now will still be required for the remaining part.[31] In addition, a large-scale implementation would mean the construction of new plants with a hazard potential comparable to reprocessing plants (nuclide separation), plants for fuel production (target production), and particle accelerators or nuclear power plants (neutron irradiation).

As an alternative to geological disposal, which must be a passively safe system after closure, supervised storage is discussed over several hundred years either above ground or in an open repository.[32] The arguments are that future generations could then continue to use recyclable materials contained in waste with better technologies or reduce the risk to the waste. However, this also means that future generations will have to deal with this issue and will have to find the resources to do so.[33] In addition, a few hundred years are neither planable nor manageable in view of historical developments: economic and social developments, war and terror or even climate change can lead to incalculable risks. According to current knowledge, several generations are already involved in the disposal of radioactive waste, and will continue to be so, since the implementation of final disposal will take at least decades. In order not to extend the burden, a timely end to active measures should be sought.

Summary

Worldwide waste management concepts include still big challenges especially for high-level waste. A disposal facility for high-level waste is not yet in operation. Storage time will be extended on uncertain timeframes with unclear consequences. Despite of negative examples of failed selection procedures or abandoned

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[29] Sandia National Laboratories: Deep Borehole Disposal Research: Demonstration Site Selection Guidelines, Borehole Seals Design, and RD&D Needs, 2013, see https://www.energy.gov/ne/downloads/deep-borehole-disposal-research-demonstration-site-selection-guidelines-borehole-seals

[30] See https://www.energy.gov/articles/studying-feasibility-deep-boreholes

[31] Öko-Institut e.V., Universität Hamburg – Zentrum für Naturwissenschaft und Friedensforschung: Gutachten Transmutation, K-MAT 48, 2015

[32] ENTRIA-Arbeitsbericht-01: Darstellung von Entsorgungsoptionen. Detlef Appel, Jürgen Kreusch und Wolfgang Neumann, Hannover, 2017

[33] Öko-Institut e.V., TÜV Nord: Gutachten zur Langzeitzwischenlagerung abgebrannter Brennelemente und verglaster Abfälle, 2015

repositories, there is no foreseeable possible alternative to a deep geological disposal.

The waste management paths for low and intermediate-level waste are also not fully developed and involve uncertainties. An additional difficulty here is the diversity of waste types and their treatment, which in turn has consequences for storage and disposal.

In general, it is challenging to compare solutions and progress in waste management of different countries because of the different technical concepts and also the chosen processes to go forward.