Disposal of Low- and Intermediate-Level Waste:

International experience

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Table of contents

Executive summary

The radioactive waste management programs of many countries include a variety of disposal concepts, tailored for different categories of waste. Some of these facilities have been operating for many decades. They range from purpose-built new construction on surface, near-surface or at depth to conversions of old mine excavations (or adding purpose-built new rooms to old mines) and other types of facilities. In almost all cases, there is a coordinated national strategy regarding the long-term disposition of all levels of radioactive waste.

In some countries, decisions have been made to construct separate repositories for each waste type at different sites, while other countries plan to dispose of two or more waste types in a combined repository or locate multiple repositories at a single site. The different approaches have been chosen for a variety of reasons such as size of waste inventory, societal preferences about number, location and type of disposal facilities; transportation issues; physical security; national policies; limited options for siting and availability of technically suitable sites; cost minimization; and general societal issues such as regional employment, infrastructure availability, etc.

As of 2020, there are existing repositories, of various designs, at various depths and in various host geologies, for all waste types except used nuclear fuel. (However, one such repository for used fuel is currently under construction in Finland). Many of the proposed used fuel repositories in different countries include provisions for the emplacement of long-lived intermediate-level waste and/or high-level waste in a part of the facility or in a co-located facility (for example, at a different depth or in a different targeted host rock formation at the same site).

The design, location and depth of a repository is often based on a combination of targeted geological formations (for example, suitable host rock layers to provide natural barriers) and degree of physical isolation required (for example, deeper implies longer isolation times, less reliance on long-term institutional controls and more resistance to inadvertent human intrusion).

The type of facilities chosen for various types of waste is closely linked to how a country classifies its radioactive waste. In countries where a decision has been made to build separate facilities for each waste type, the classification system along with the treatment and conditioning of the waste is geared towards distinguishing between the different waste types suitable for each type of disposal (for example, short-lived wastes for surface or near-surface, long-lived wastes for deeper disposal). In countries opting for a combined deep disposal facility, there is generally less of a need to distinguish between categories, and their classification systems reflect this. Co-disposal of multiple categories of waste in the same facility is an important concept that can reduce overall waste management costs by reducing the number of disposal facilities required and simplifying the pre-disposal management of radioactive wastes.

Surface and near-surface repositories for L&ILW (as well as some deeper repositories in fractured host rock) tend to rely on multiple engineered barriers for radionuclide containment, such as engineered waste forms, backfill, cap and cover systems, etc. Deeper repositories for L&ILW in unfractured rock tend to rely more on natural barriers such as the host rock and surrounding geosphere (for example, cap rock layers) than on additional engineered barriers. Planned repositories for HLW and used nuclear fuel employ a combination of natural and engineered barriers. In all cases, the choice of barriers is waste and site specific, depending on the safety case for the repository.

There is also a trend in many countries to move towards selecting simpler geological settings that are relatively uniform and easy to characterize, such as sedimentary formations, where they are available in that country. These simpler geological settings provide added confidence in the modeling required for the long-term safety assessments.

In a few cases, previous disposal practices do not meet current expectations and remediation of the sites has been performed or is being contemplated, up to and including retrieval of the waste for further treatment and/or disposal in a different facility.

For countries with major nuclear power programs, the main trends are:

- They have coordinated national policies for radioactive waste management, often implemented by a single organization.

- Surface or near-surface repositories are often used for very low-level wastes and short-lived L&ILW. In some countries, multiple sites may exist for such wastes, while other countries have opted to have one national repository site.

- Deep repositories are recognized internationally as the preferred option for long-lived L&ILW. In some cases, this may be combined with short-lived waste to have the convenience of "one site" for L&ILW and to minimize the pre-disposal waste handling and segregation requirements. In other cases, it is planned to be combined with HLW and/or used nuclear fuel because they already have existing facilities for short-lived waste and combining with HLW or used fuel provides a reasonable reference case for financial planning purposes. However, such combinations can place some additional technical constraints on the design of the repository due to the properties of the different waste types and how they may interact with each other over the long-term.

1 Background

It is commonly recognized that the nuclear fuel cycle results in the generation of radioactive waste in a variety of forms, characteristics and hazard levels. This results from the operation and eventual decommissioning of nuclear fuel cycle facilities, reactors, research facilities and other support facilities where radioactive materials are used or produced. In addition, radioactive waste is also generated by other activities and facilities such as universities and research centres; hospital and laboratory medical diagnostic procedures; and the industrial production and use of radioisotopes and sealed radiation sources. Radioactive waste can also arise from remediation of contaminated lands and facilities, for example, areas affected by accidents or past practices which do not meet current safety standards.

Waste can be divided into different categories, based on the level of the hazard and its duration. Over time, the radioactivity will decrease naturally as the radionuclides undergo decay and eventually convert into a stable (that is, non-radioactive) form. The length of time required to reach this state varies greatly depending on the half-life of the specific radionuclide involved, which can range from fractions of a second to millions of years or more, as well as the length of its decay chain (that is, the number of decay steps it undergoes before reaching a stable state).

The various categories of waste must be managed appropriately to protect human health and the broader environment from the radioactivity and any other hazardous components it may contain. There are many options available for the safe long-term management of different categories of radioactive wastes according to their hazard levels and the required duration of isolation. Co-disposal of multiple categories of waste in the same facility is an important concept that can reduce overall waste management costs by reducing the number of disposal facilities required and simplifying the pre-disposal management of radioactive wastes. In such a concept, the repository must be designed to safely contain the highest class of waste destined to be disposed in the facility. If this can be achieved, then lower classes of waste can also be safely disposed in the facility.

As discussed in this paper, numerous countries have implemented, or are planning to implement, a variety of approaches for managing their wastes.

Some waste (referred to as "long-lived radioactive waste") requires containment and isolation from the biosphere for millennia. Many countries define "long-lived" as having a half-life greater than that of Cs-137 (Cs-137 is a major fission product with a half-life of about 30 years). This type of waste normally implies a deep (geologic) facility that relies on the host rock formation as one of the main barriers to provide control of radionuclide migration, physical isolation and protection from inadvertent human intrusion for extended periods of time until the radioactivity has decayed to low enough levels. Other engineered barriers, such as waste form and packaging can be added to enhance the natural barriers as required.

A surface or "near-surface"[1] disposal facility is generally designed around a hazardous life-time for the waste of about 300 years (the equivalent to about ten half-lives of Cs-137). This may seem like a long time, but 10 half-lives is only a reduction by a factor of about 1000 ($2^{10} = 1024$). While this reduction

[1] Note that there is no universal definition of "near-surface". However, in radioactive waste disposal it is generally understood to mean depths of less than a few tens of metres below ground surface [IAEA 2020b].

factor is generally enough to reduce low-level wastes to an innocuous level, it is usually not adequate for intermediate-level or high-level wastes which may start out with orders of magnitude higher levels of Cs-137 than LLW. Therefore, much longer protection times are required when dealing with ILW and HLW, even if they only contain “short-lived” radionuclides due to the high initial concentration of these radionuclides.

Canada has a robust regulatory regime and policy framework for the long-term management and disposal of radioactive waste, specifically under the Nuclear Safety and Control Act, the Nuclear Fuel Waste Act and under the 1996 Radioactive Waste Policy Framework. This framework provides a set of principles governing the long-term management and disposal of radioactive waste and includes a clear assignment of the roles and responsibilities of both the federal government and waste owners [LOP 2020]. In Canada, producers of radioactive wastes (often called the “waste owners”) are responsible for the life-cycle management of their wastes, including disposal. For low- and intermediate-level wastes, individual waste owners are developing their own plans according to the above Federal policy.

The main focus of this paper is on the disposal of low- and intermediate-level wastes. Other waste categories are mentioned when necessary to maintain the context of how wastes are managed overall in various countries.

2 Waste classification and characteristics

2.1 Waste classification

One of the fundamental aspects of safe and cost-effective radioactive waste management is to categorize the various wastes in a systematic way, based on properties that are important for the design, operation and safety case of the waste management facilities. There is a wide variety of waste classification systems in use around the world. It is important to note the link between the disposition of the waste (either existing or planned) and the classification system in use. Each country has built a classification system based on their waste management strategies and existing or planned infrastructure. While many of the classification systems are outwardly similar in terminology and structure, they generally differ in the fine details, such as the numeric boundaries between different classes of waste.

In Canada, radioactive waste classes are defined in CSA standard N292.0 [CSA 2019] and have also been included in the recent CNSC REGDOC-2.11.1 [CNSC 2021]. The classification system, which consists of low-level waste (LLW), intermediate-level waste (ILW), high-level waste (HLW) and uranium mining and milling waste (UMM), is further described in Appendix E. This paper focuses on the LLW and ILW classes.

A definitive numerical boundary between the various classes of radioactive waste (primarily LLW and ILW) is not provided in the CSA standard, since activity limitations differ between individual radionuclides or radionuclide groups and will be dependent on both short- and long-term safety-management considerations. A contact dose rate of about 2 mSv/h has been used, in some cases, to distinguish between low-and intermediate-level radioactive waste.

Despite the CSA classification system, most existing waste in Canada has been classified under a variety of older systems which were established prior to the creation of the CSA standard by each waste owner. The major waste owners in Canada (OPG, AECL, NB Power, and Hydro-Québec) all have their own historical classification systems with slightly different numerical boundaries between classes based on the capabilities of their waste management and storage systems.

Internationally, most of the classification systems used around the world recognize broad categories of radioactive waste, such as low- and intermediate-level waste (L&ILW) (which is sometimes further subdivided into low-level waste (LLW) and intermediate-level waste (ILW)); high-level waste (HLW); and used nuclear fuel (UF). (Note that some countries do not consider used nuclear fuel to be a waste and have a policy to reprocess and recycle the fissile content of the used fuel into additional reactor fuel. The reprocessing results in the production of HLW as well as additional LLW and ILW).

Some countries further subdivide the L&ILW into long-lived (LL) and short-lived (SL). Although the exact definitions vary, the general approach is that long-lived waste contains significant quantities of radionuclides with half-lives of greater than about 30 years (that is, greater than the half-life of Cs-137 or Sr-90, two of the most common fission products in nuclear reactor waste). The limit on “significant quantities” is radionuclide and repository concept specific and is typically derived from a safety assessment for a near-surface repository in which the total radioactivity in the waste decays to low enough levels within an institutional control period (typically 300 years ≈10 half-lives of Cs-137 or Sr-90) such that the scenario does not result in excessive radiation dose (for example, due to degradation of the engineered barriers over time) as defined by the country’s regulations or safety criteria. The long-lived radionuclides (for example, C-14 with a half-life of about 5700 years) require isolation for much longer time periods to decay to low enough levels. Therefore, the quantities of these radionuclides must be restricted in some repository concepts, especially near-surface ones.

Some countries have additional categories, such as naturally occurring radioactive materials (NORM), uranium mining and milling waste (UMM), very low-level waste (VLLW), very short-lived waste (VSLW) and transuranic (TRU) waste. UMM is generally managed in engineered surface facilities, due to its large volume and relatively low hazard. UMM is not discussed further in this paper. VLLW is often managed in very simple surface facilities, due to the low hazard. VSLW is normally stored for a short period of time to allow the radionuclides to decay, then is treated as normal industrial type waste. TRU waste, which contains high concentrations of actinides, is generally handled as long-lived waste (for example, in a deep repository). Further details about the various waste classification systems in use around the world can be found in [IAEA 2018].

The IAEA has attempted to unify the definitions for international reporting purposes and has proposed a standard classification system in its GSG-1 standard [IAEA 2009], based on six waste categories:

- Exempt Waste (EW)
- Very Short-Lived Waste (VSLW)
- Very Low-Level Waste (VLLW)
- Low-Level Waste (LLW)
- Intermediate-Level Waste (ILW)
- High-Level Waste (HLW)

The IAEA classification system is based on minimum disposal requirements based on radiological safety considerations, with an increasing degree of isolation from the biosphere through the use of natural and/or engineered barriers required for higher levels and longer lived waste. Further details can be found in Appendix E.

It should be noted that in instances where it is planned to dispose of all LLW and ILW in the same repository (normally a deep facility), there is generally no operational need to distinguish between long-lived wastes (ILW) and short-lived wastes (LLW), and the waste classification systems in use for these facilities normally reflect that point.

For countries that use near-surface repositories, there is a need to make this distinction in order to be able to exclude the long-lived wastes from the near-surface facility. This also requires more extensive characterization efforts for each waste package to ensure that it meets the restrictions imposed by the near-surface repository.

For the purposes of consistent presentation among disposal concepts and countries in this paper, the wastes have been grouped into VLLW (Very Low-Level Waste), LLW (Low-Level Waste), ILW (Intermediate-Level Waste), and HLW (High-Level Waste)/UF (Used Nuclear Fuel), similar to IAEA GSG-1, even if individual countries classify their wastes differently.

Another important aspect that is not included in the basic radioactive waste classification system is the chemical toxicity of the waste [IAEA 2002]. In addition to the radiation hazard, many radioactive waste types also contain chemically hazardous elements, such as heavy metals and organic chemicals. While the radioactivity will naturally decay over time and most organic chemicals will degrade over time due to microbial and other reactions, many chemical hazards (such as heavy metals) remain hazardous essentially forever. In some cases, it is these chemical hazards that may dictate the length of time and degree of isolation of the waste required rather than the radioactivity considerations. Note that while many of the heavy metals occur in nature, they may be present in the waste in elevated or concentrated levels.

2.2 Low-level waste

The majority of the LLW in Canada consists of contaminated soils and related waste from the early operation of the radium industry (in some other countries, much of this waste would be considered to be very low-level waste (VLLW) or naturally occurring radioactive materials (NORM)). The remainder of the LLW in Canada includes contaminated materials, tools, equipment, rags, protective clothing, etc. from the operation, maintenance and decommissioning of nuclear facilities or other facilities where radioactive materials are used. (These wastes are similar to those produced in any other industry, except they are contaminated with small amounts of radioactivity [NEA 2010].)

At the end of 2016, there were approximately 2.4 million m^3 of LLW stored in Canada, of which about 1.7 million m^3 were historic soils and related wastes (~73% of the total), with the remaining 27% being wastes from on-going nuclear activities [NRCan 2018][2], including ~526,000 m^3 at AECL-owned facilities (mostly Chalk River[3]); 83,000 m^3 at OPG's Western Waste Management Facility and the remainder at various other nuclear facilities in Canada. See Appendix B for further details on waste quantities.

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[2] Note that all waste inventory volumes given in this report are generally based on the 2018 6th Review for IAEA Joint Convention which are the latest publicly available at the time this report was prepared. The Joint Convention reviews are done on a 3-year cycle with the 7th Review occurring later in 2021. Inventory data will be updated after the 7th Review reports are made public.

[3] AECL facilities are managed by Canadian Nuclear Laboratories (CNL) under a Government-owned Contractor-operated (GoCo) model.

Additional information regarding the characteristics of typical CANDU nuclear power plant LLW can be found in [OPG 2010].

Currently, LLW is safely managed throughout Canada either *in situ* or at interim storage or long-term management facilities (see Appendix A for a map of locations). The wastes are packaged in a variety of containers and stored in above-ground and below-ground storage facilities. Typical containers used in Canada for nuclear power plant wastes are described in [OPG 2010].

2.3 Intermediate-level waste

The ILW in Canada consists of filters and ion exchange resins used in the water purification circuits of nuclear power plants along with replaced reactor core components and some high activity radioactive sources used in radiotherapy. ILW generally requires shielding due to high radiation levels, but little or no provision for heat dissipation during its handling, transportation and long-term management. However, some ILW (for example, core components from reactor refurbishment) may require heat management in the short term because of its total radioactivity level.

At the end of 2016, there were approximately 33,000 m^3 of ILW stored in Canada, of which about 20,000 m^3 was at AECL-owned Chalk River site, followed by about 12,000 m^3 at OPG sites (mostly at the Western Waste Management Facility). The remainder of about 1,000 m^3 was stored at the other nuclear sites in Canada [NRCan 2018]. See Appendix B for further details on waste quantities. Additional information regarding the characteristics of typical CANDU nuclear power plant ILW can be found in [OPG 2010].

Currently, ILW is safely managed throughout Canada at interim storage facilities (see Appendix A for a map of locations). The wastes are packaged in a variety of containers and stored in above-ground and below-ground storage facilities. Typical containers used in Canada for nuclear power plant wastes are described in [OPG 2010].

2.4 Waste Acceptance Criteria

Disposal Waste Acceptance Criteria (WAC) are quantitative or qualitative criteria that radioactive waste must meet in order to be accepted by the operator of a repository for disposal. WAC might include, for example, restrictions on physical condition of the waste (for example, physical state, dimensions, mass, etc.); the activity concentration or total activity of particular radionuclides (or types of radionuclide) in the waste; restrictions or exclusions on certain chemical species in the waste packages (for example, chelating agents, toxic chemicals, etc.) and/or requirements concerning the waste form or packaging of the waste (for example, conditioning matrix, use of standard containers, compressive strength, leach resistance, etc.).

WAC are normally facility-specific. They are used to ensure that any waste accepted at the facility will be in compliance with its safety case and licensing conditions. The development of waste acceptance criteria should be carried out in parallel with the development of the disposal route. WAC should be derived from consideration of both operational requirements (for example, handling) as well as those contained in the site-specific safety assessment for a repository. These criteria should be qualitatively or quantitatively based such that conformance can either be assessed by direct measurement and/or assured by application of appropriate quality assurance methods and inspections during the waste management process.

Note that because WAC are facility-specific, the WAC developed for one facility are not necessarily transferable to another facility, even one of similar design. However, while the specific limits and restrictions will vary from facility to facility, the categories and types of requirements included in a WAC are very similar in most cases. An understanding of these generic requirements can be very helpful in guiding a waste characterization program and subsequently in the development of a facility specific WAC.

WAC are generally developed in an iterative manner, along with the design and safety assessment of the disposal facility. Once a facility is operational, the WAC must be reviewed on a regular basis to ensure that they are still valid or to account for any changes in the safety case, licensing conditions or new waste forms that may be considered.

3 Basic disposal concepts

A wide range of disposal concepts have been developed around the world for various types of radioactive waste, according to the needs and available infrastructure of the country [NEA 2010, IAEA 2020b]. These are described below, grouped according to their basic design features. Further details about typical facilities of various designs can be found in Appendix F.

3.1 Trench

Trenches can range from simple, unlined designs excavated in various soils to ones with highly engineered barrier and cap systems. Historically, simple trenches were used for radioactive waste disposal in most countries in the early years of the nuclear era. They were inexpensive and easy to construct and operate. They were typically located at or near the nuclear facility that produced the waste. Unfortunately, very few (if any) records were kept concerning the types, characteristics and quantities of wastes that were disposed in these early facilities [IAEA 2007].

Trenches are considered to be “near-surface” facilities and are still commonly used in many countries for high volume, low hazard wastes [IAEA 2017]. They are generally considered appropriate only for wastes that will decay sufficiently within an anticipated period of institutional control (generally between 100 and 300 years) to represent no risk to the public, as determined by safety assessments.

Temporary weather covers can be used during the loading phase to protect the wastes and trench structure and to minimize water ingress from precipitation. Spaces between waste packages can be backfilled with soil, sand, gravel or concrete prior to capping.

Older designs typically did not have any form of engineered barriers, such as drainage systems, liners or multi-layered capping systems. Modern designs typically include all of these features, such as the French CIRES facility near Morvilliers shown in Figure 1. The facility has been in operation since 2003 and consists of a series of lined trench type disposal cells, each up to 124 m long x 26 m wide x 8.5 m deep, with a net capacity of up to 25,000 m^3 per cell and 650,000 m^3 for the currently licenced facility [ANDRA 2014]. To the end of 2016, approximately 330,000 m^3 of VLLW has been disposed of at CIRES [ANDRA 2018].

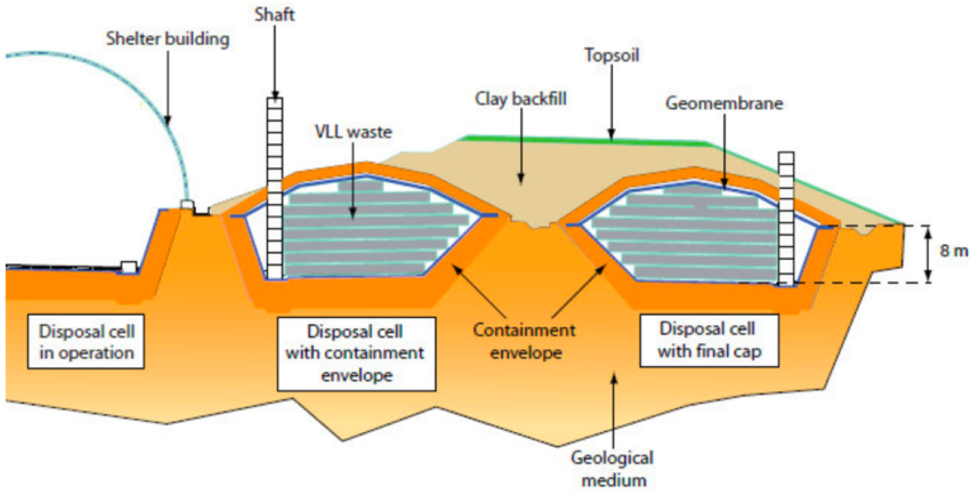

FIGURE 1: Schematic of the CIRES VLLW Disposal Facility near Morvilliers, France [USDOE 2011]

A similar design is also used in Spain at the El Cabril site for VLLW disposal.

Other trench designs are used in the USA for LLW at the Barnwell, South Carolina; Clive, Utah; Andrews County, Texas and Hanford, Washington commercial disposal facilities, as well as at several Department of Energy sites and historically at several other commercial disposal facilities (now closed). A total of approximately 26 million m^3 of LLW of have been disposed of in various trench facilities in the US [USDOE 2017].

The newest repository for commercial LLW in the US is the Waste Control Specialists (WCS) facility in Andrews County, TX which began operation in the spring of 2012. It consists of concrete-lined trenches excavated in an arid location, in a 150 m thick bed of impermeable red clay. It includes two adjacent repositories of similar design: one for commercial wastes and the other for US federal government wastes. A typical trench and cover design is shown in Figure 2. The overall dimensions of the commercial repository are about 275 m x 275 m x 25 m deep, which will be developed in four stages with a capacity of about 76,000 m^3 per stage. Wastes are placed in cubic or cylindrical concrete packages prior to emplacement. These waste packages are grouted and stacked to a height of about 15 m from the trench floor (nominally 4 layers of concrete packages). The space between packages is backfilled with sand. Once filled, the trench stage will be capped with a concrete cap, then a multi-layer engineered cover system. The depth of the WCS trenches allows all US classes of LLW, including the most radioactive classification (Class C), to be disposed. As of December 2016, the WCS facility contained about 195,000 m^3 of waste [USDOE 2017].

Trenches were also used in the United Kingdom (at Drigg), where some 800,000 m^3 of LLW was disposed in clay-lined trenches between 1959 and 1995 (more recently, large concrete vaults have been constructed at Drigg since 1988). Other countries which have used trench disposal for VLLW or LLW include Argentina, China, France, India, Japan, Norway, Russia, Slovakia, and South Africa [IAEA 2007; IAEA 2018; USDOE 2011]. Some of the older facilities have been found to not meet adequate safety standards and have required remediation (for example, CEA Cadarache, France; Kurchatov Institute, Russia; Kjeller, Norway) [IAEA 2007].

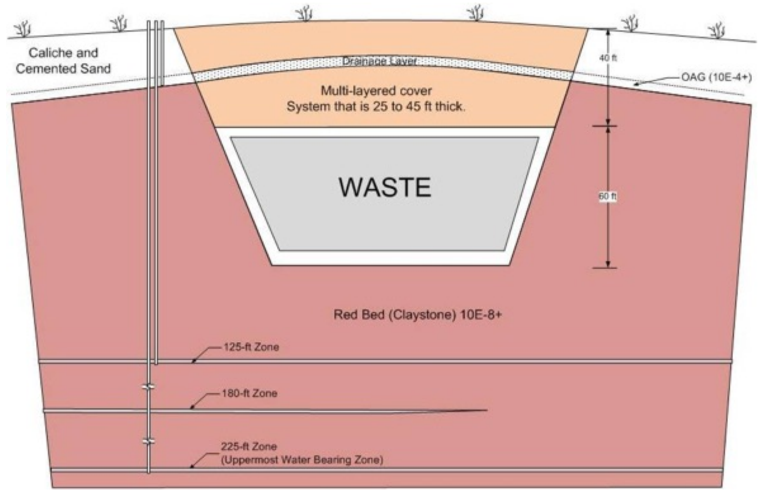

FIGURE 2: Typical WCS trench design for LLW, Texas [WCS 2020]

3.2 Aboveground mound

An aboveground mound is in some respects very similar to a trench, except it is built on the surface of the ground, then mounded over with a cap and cover system. Aboveground mounds are generally considered to be surface facilities, although they are sometimes included in the "near-surface" category.

Temporary weather covers can be used during the loading phase to protect the wastes and to minimize water ingress from precipitation. Spaces between waste packages can be backfilled with soil, sand, gravel or concrete prior to capping and covering.

Internationally, the aboveground mound has been used for VLLW disposal (for example, at most nuclear reactor sites in Sweden) and LLW disposal (for example, Clive Utah, USA; Fernald Ohio, USA; and CSM La Manche, France). It is currently used in Canada for historic LLW (for example, Port Hope Ontario [PHAI 2018]), and has been proposed by Canadian Nuclear Laboratories for disposal of ~1 million m^3 of LLW at the Chalk River site.

Figure 3 [USDOE 2011] shows the VLLW mound type disposal facility for short-lived waste (which will decay to clearance levels within about 50 years) at the Oskarshamn Nuclear Power Plant in Sweden. The disposal cells at Oskarshamn are constructed on a base of about 3000 m^2. A concrete pad with drainage channels is installed at the bottom of the disposal mound. Wastes are stacked on the pad in various containers ranging from large bags to ISO freight containers. When a disposal area has been filled, a cover and cap system is constructed over the waste pile, consisting of various layers of membranes, bentonite, and drainage layers, topped with a 1 m rubble and soil cover. Large concrete blocks are used around the perimeter of the mound to anchor the cover layers and to provide some added structural stability to the mound.

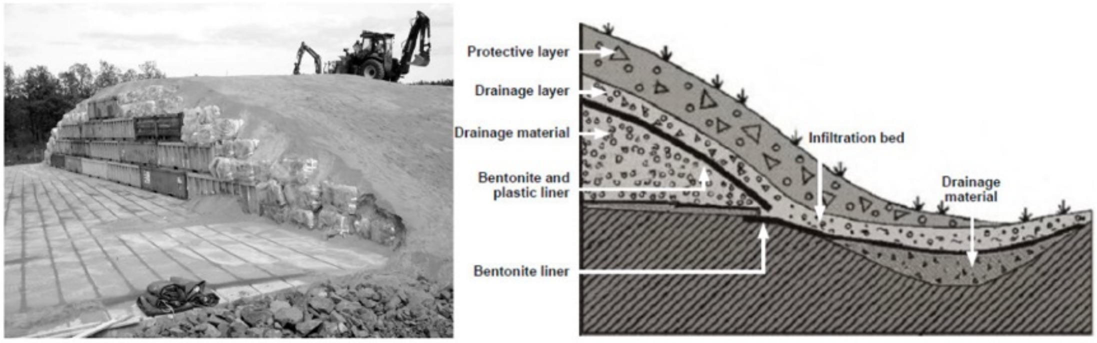

FIGURE 3: VLLW disposal facility at Oskarshamn Nuclear Power Plant [USDOE 2011]

In France, an early repository for short-lived L&ILW was built at Centre de la Manche (CSM) adjacent to the La Hague spent fuel reprocessing plant in northern France. It has been under closure and monitoring since 1994. CSM started operation in 1969 and contains about 527,000 m^3 of waste. The waste containers were stacked directly on concrete slabs, as shown in Figure 4 [USDOE 2011]. The higher activity wastes were placed in concrete bunkers built on those slabs. Spaces between containers are backfilled with sand, gravel or concrete. The repository occupies a site of about 15 ha and was covered in 1997 with a multi-layer capping system including a bitumen membrane and a combination of drainage and impermeable layers designed to prevent water seepage into the repository. The top cover layer was planted with grass in order to promote the evaporation of rainwater and to prevent the weathering and erosion of the upper layers of the engineered cover.

FIGURE 4: Waste emplacement at CSM Disposal Facility in France [USDOE 2011]

Aboveground mounds have also been used at several locations in the USA, such as Fernald, Ohio. The former US Department of Energy Feed Material Production Center in Fernald Ohio operated from 1951 to 1989 as a uranium processing facility. It underwent decommissioning and environmental restoration in the 1990s and early 2000s, and several on-site radioactive waste disposal facilities were developed. The largest of these is an aboveground mound which holds approximately 2.3 million m^3 of LLW. Materials disposed in the facility consist of about 85% soil and similar materials, and about 15% building demolition debris, decommissioned equipment, and other miscellaneous LLW. The basic design requirement for the facility was to isolate the wastes from the environment “for up to 1,000 years to the extent reasonably achievable, and, in any case, for 200 years” [ICCHGE 2008]. The mound consists of 8 cells in a row, with total dimensions of about 240 m wide x 1130 m long x 20 m high, and sits on a multi-layer engineered base liner (approx. 1.8 m thick) with alternating isolation and drainage layers, as shown in Figure 5. The final engineered cover is about 3 m thick, which also contains isolating and drainage layers as shown in Figure 6. The facility was completed (capped) in 2006 and is now in long-term surveillance mode.

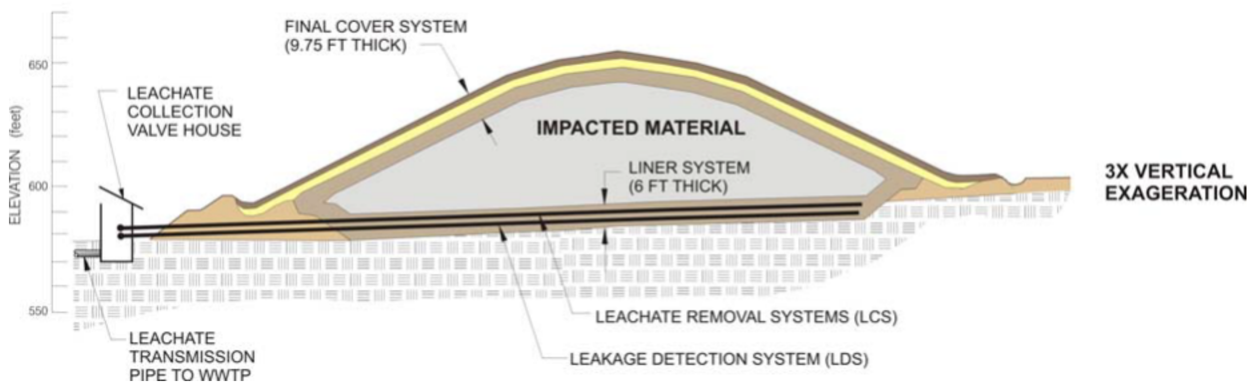

FIGURE 5: Cross-section of Fernald On-site Disposal Facility Mound [ICCHGE 2008]

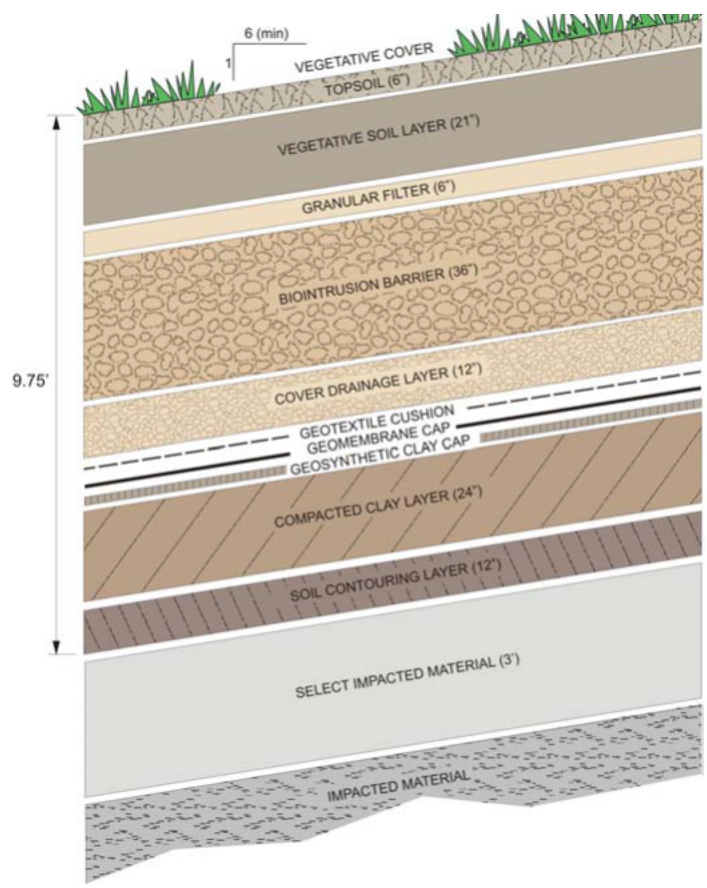

FIGURE 6: Detail of Fernald On-site Disposal Facility Mound engineered cover [ICCHGE 2008]

3.3 Concrete vault

Concrete vaults are one of the most common methods used in the world today for disposal of LLW [IAEA 2018]. They are modular in nature, so can be scaled to a range of small to very large capacities, and offer the flexibility to accept a wide variety of waste package sizes, including very large and heavy objects such as steam generators and reactor pressure vessels. They can also be constructed in a variety of geological settings at surface or near-surface at various depths up to several tens of metres. The basic vault consists of a thick-walled concrete structure of various dimensions, often with a built-in drainage and/or water monitoring system.

Vaults are typically filled with waste packages from either the top (using a fixed or mobile crane) or side (using a forklift or similar vehicle), then covered with a concrete cap and engineered multi-layered cover system when full. Temporary weather covers can be used during the loading phase to protect the wastes and the structure and to minimize water ingress from precipitation. Spaces between waste packages are typically backfilled with sand, gravel or concrete to form a monolithic structure prior to capping.

3.3.1 Surface vaults

The classic example of a concrete vault type disposal facility located at ground surface is the Centre de l'Aube facility in France (known by the French acronym CSFMA - le Centre de stockage des déchets de faible et moyenne activité), which consists of a series of above-ground concrete vaults, as shown in Figure 7. The total licenced capacity is 1,000,000 m^3 in 400 disposal vaults (25 m x 25 m x 8 m high). The vaults are designed for a 300-year life and will be capped with an engineered cover system once they have been filled. To the end of 2016, the facility contained approximately 325,000 m^3 of waste.

FIGURE 7: Aerial view of the CSFMA repository for short-lived L&ILW, France [SKB 2011]

LLW containers (mostly drums) are stacked in the vaults with an overhead crane. A moveable weather cover is used to protect open vaults during the loading stage. The vaults are then backfilled with concrete, layer-by-layer, as shown in Figure 8, left. A reinforced concrete cap is poured on top once the vault has been filled.

FIGURE 8: Backfilling of CSFMA LLW vault with concrete (L) and ILW vault with gravel (R) [NOS 2014]

For short-lived ILW, most wastes are grouted into cylindrical or cubic fibre-reinforced concrete containers, and the vaults are backfilled with gravel, as shown in Figure 8, right.

The El Cabril L&ILW repository for short-lived waste in Spain started operation in 1992 and is similar in design to the French Centre de l'Aube repository. Unlike the French facility, waste drums are first placed in 1.2 m x 1.2 m x 1.2 m (typically holding 4 x 200-L drums) or 2.25 m x 2.25 m x 2.20 m concrete containers (typically holding 18 x 200 L drums). Some of the drums may be first supercompacted, which allows up to 40 supercompacted pucks to be placed into the larger concrete container. When a container is full, contents are immobilized by concrete grout and the solidified block is placed in the disposal cell. Lower activity drums can also be placed in similar sized steel racks, typically holding 6 drums, instead of the concrete box. The disposal cells are 24 m x 19 m x 9 m high, optimized for the dimensions of the disposal containers. The walls and base of the cells are about 0.5 m thick concrete.

Once the disposal cell is filled with containers, the upper reinforced concrete closure slab is constructed and weatherproofed. Once all the disposal cells are filled, they will be covered with a multi-layer engineered cap system and vegetated.

Currently, there are 28 disposal vaults with a capacity of about 37,000 m^3. The forecast total capacity requirement is some 90,000 m^3, requiring about 50 additional disposal cells. These would be constructed in blocks as required. As of December 2016, approximately 32,000 m^3 is disposed in the facility.

3.3.2 Shallow near-surface vaults

Concrete vault disposal facilities have also been constructed underground at various depths. The most common is at a shallow depth[4] (up to a few metres below ground surface). In some respects, these are similar to trenches, but consist of a series of discrete concrete vaults constructed in the excavation. They are accessed from above, and waste packages are loaded with a fixed or mobile crane. Similar to the aboveground vault concept, the near-surface underground vaults are typically designed for a 300 year life and would be capped with an engineered cover system once they have been filled.

An example of the shallow near-surface vault can be found in Slovakia. The National Repository for short-lived L&ILW (RU RAO) is located near Mochovce, adjacent to the nuclear power plant. It is designed for disposal of solid and solidified short-lived L&ILW produced during the operation of nuclear

[4]Note that the terms "shallow" and "deep" are not precisely defined and may mean different things in different contexts or countries.

installations including the reactors at Mochovce and Jaslovské Bohunice. The repository is built on a geological formation with low permeability and high sorption capacity. An engineered layer of compacted clay underneath the disposal vaults provides an additional barrier against radionuclide migration. A monitored drainage system collects any water seepages in the individual disposal vaults.

Shown in Figure 9, the repository consists of concrete disposal vaults arranged into double rows of 40 vaults (2 x 20) with a movable weather roof that is used during loading operations. Each vault is 6 m x 5.5 m x 18 m L with 0.6 m thick walls and has a capacity of 90 fibre-reinforced concrete containers (1.7 m x 1.7 m x 1.7 m external, 3.1 m^3 internal volume), for a total capacity of 7200 containers (22,320 m^3 of waste) per double row covering a total area of 11.2 ha. The repository site allows for expansion up to 7.5 double rows of disposal vaults. This is forecast to be adequate for all of the operational and decommissioning waste from existing reactor units [JAVYS 2019].

Drums of compacted and bituminized wastes are grouted into the concrete containers with a cement mixture, some of which may be formed from radioactive liquid waste. A weather cover is used over the entire double row of open vaults as they are being filled. Once filled, the vaults are backfilled and capped with concrete. At closure, the repository will be capped with a multi-layer engineering capping system.

The first double row has been in operation since 2001. At the end of 2016, the repository contained 4,804 concrete disposal containers representing a total volume of about 14,900 m^3. The second double row has been in operation since 2016 and construction of a third double row is started in 2019.

FIGURE 9: Mochovce repository for short-lived L&ILW, Slovakia [JAVYS 2019]

A similar repository has been in operation in the Czech Republic since 1995. The near-surface repository for short-lived nuclear power plant L&ILW, located adjacent to the Dukovany nuclear power plant site, consists of 112 reinforced concrete vaults, arranged in four rows of 28, with a total capacity of 55,000 m^3. The vaults are 5.3 m x 5.4 m x 17.3 m. The Dukovany repository is sited on impermeable Quaternary clay sediments. It is above the underground water table and has a double drainage system to control water collection in and around the repository vaults. Wastes, mostly in 200 L galvanized steel drums, are emplaced using a travelling gantry crane with a shielded operator cab. The inventory at the end of 2016 was approximately 11,520 m^3. Once each vault is full, the space between the drums is filled with concrete backfill and the vault is covered with a thick sheet of polyethylene, which prevents rainwater from infiltrating the vault. Each vault is then covered with a thick concrete panel. A post-closure institutional control period of 300 years is planned.

3.3.3 Deeper near-surface vaults

An example of a deeper near-surface vault is the Japanese repository for short-lived L&ILW, located on the Japan Nuclear Fuels Ltd. (JNFL) complex at Rokkasho-mura. It has been in operation since 1992 and consists of two disposal facilities, each with a number of concrete structures constructed in a large pit excavated in the bedrock. In the "Number 1 Disposal Facility" for homogeneous solidified waste (for example, ion-exchange resins and evaporator concentrates), each structure is approximately 24 m x 24 m x 6 m high, excavated to a depth of about 15 m below surface. The structures are divided into cells, approximately 6 m x 6 m, and can each hold up to 320 standard 200 L drums (8 layers of 8x5 grid of drums in each cell). In the "Number 2 Disposal Facility", which began operation in the year 2000 for compacted and solidified wastes (for example, metals and concrete), the structures are 36 m x 37 m x 7 m high, excavated to a depth of about 20 m below surface and contain 36 cells of 6 m x 6 m, each holding up to 360 drums (9 layers of 8x5 grid). The currently installed capacity is 40,000 m^3 for each facility. The facilities are expanded in stages as required, with a total final design capacity of some 600,000 m^3 (3 million drums).

Wastes are generally grouted into 200-L drums. The drums are placed in layers by an automatic drum handling device and the space between drums is grouted. When a cell is filled, it is capped with a reinforced concrete lid, as shown in Figure 10. When filled, the entire area will be capped with a 4-m thick layer of bentonite and soil. To end of 2016, Number 1 facility contained about 147,000 drums (~29,000 m^3) and Number 2 facility about 113,000 drums (~22,600 m^3).

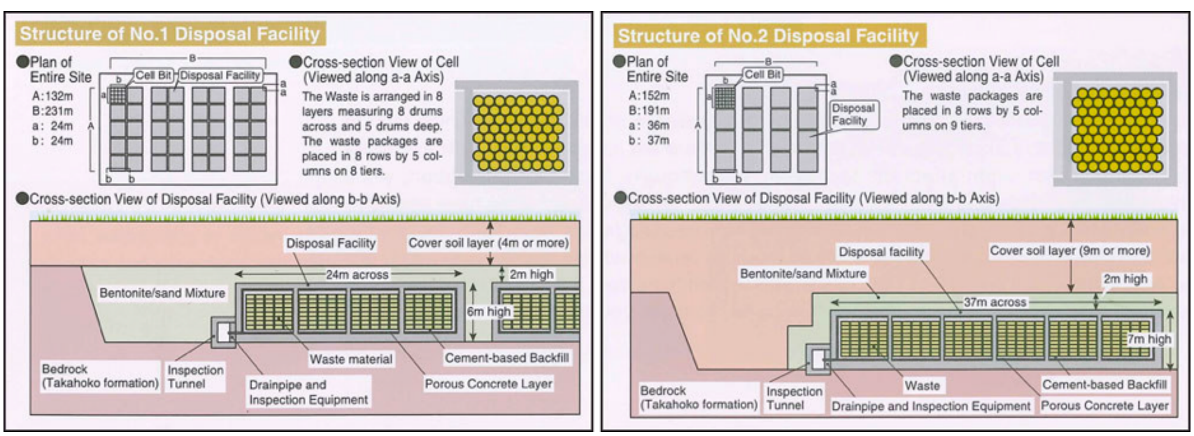

FIGURE 10: Rokkasho-mura Repository LLW, Japan [USDOE 2011]

Another example of a deeper near-surface concrete vault is the one constructed at Dounreay in Scotland that began operation in 2015. The first phase of the facility consists of a 92 m L x 46 m W x 12.5 m H concrete vault for LLW and a 66 m L x 46 m W x 12.5 m H concrete vault for high volume, low activity waste (termed HVLA in the United Kingdom) with the base approximately 16 m below ground surface but above the water table. Similar to the Drigg facility in England, the wastes are mostly in half height ISO freight (HHISO) containers stacked by forklift, giving a total capacity of 38,100 m^3 for LLW and 26,900 m^3 for HVLA. The containers for LLW are grouted prior to emplacement. Additional vaults will be added in phases 2 and 3 to accommodate a total of about 130,000 m^3 of LLW and 46,000 m^3 of HVLA, as packaged in HHISOs.

A floor drain water collection system is included in the vault design. Unlike Drigg, a weather cover is used during the loading phase to minimize water in-leakage. Containers are stacked close-packed up to 8 high. Only the front face and tops will be accessible for inspections. However, a narrow space is provided along one edge of the vault to allow remote inspection of the full length.

3.4 Rock cavern

A rock cavern repository consists of one or more underground excavations in a suitable bedrock formation. The disposal caverns are accessed by a shaft, ramp or tunnel. It can be either purpose-built new (for example, Finland, Hungary, Korea, Norway, Sweden, USA) or converted from an existing mine excavation (for example, Germany, Czech Republic, Romania, Slovakia). They have been constructed in various geological media, such as salt, sedimentary and crystalline formations at various depths[5].

Some designs include concrete vaults constructed in the excavated space, while others rely on the rock formation alone. Similar to a mine, they require a forced ventilation system to provide air to workers and machinery. The rock cavern repository generally relies on slow movement of ground water, depth and rock properties to isolate the waste from the biosphere.

Once the disposal rooms have been filled, they are generally sealed off and the entire repository is closed when full by sealing off the access ramps/shafts as well as the ventilation shafts. Some designs include backfilling of the disposal vaults, while others only seal the entry(s) to the disposal room. The sealing materials vary by design and could include concrete, clay materials, sand, bitumen, etc.

Rock caverns are generally used only for LLW and ILW. Large volume wastes such as VLLW are generally not placed in rock caverns due to the high cost of excavation and the limited speed at which most facilities can move wastes underground (especially for shaft access with a hoist).

3.4.1 Shallow rock caverns

The classic examples of purpose-built shallow depth rock cavern repositories are those in Sweden and Finland.

In Sweden, short-lived L&ILW is disposed of at the SFR repository which has been in operation since 1988, adjacent to the Forsmark Nuclear Power Plant. This facility services all of the nuclear facilities in Sweden. It is operated by SKB, a waste management company owned by the nuclear utilities. As shown in Figure 11, the repository consists of four rock caverns of various designs and dimensions and a silo, all excavated in the crystalline bedrock under the Baltic Sea at a depth of approximately 50 m below the seabed and 1 km out from the shoreline. It is accessed by a ramp and has a total capacity of about 63,000 m^3. The left side of the figure also shows a planned expansion with six new vaults for an additional 117,000 m^3 (mostly decommissioning waste) at a depth of approximately 120 to 140 m below the seabed. Pending regulatory approvals, construction of the SFR expansion is estimated to take about six years to complete.

[5] Note that some shallow depth rock caverns are sometimes included in the “near-surface” general category of repositories.

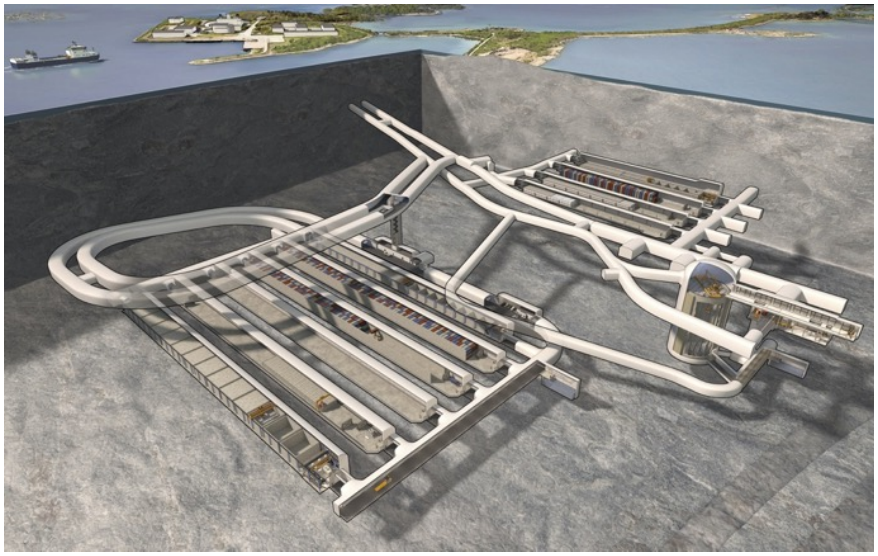

FIGURE 11: SFR Repository, Sweden [SKB 2018]

The most active wastes, with a maximum dose rate of 500 mSv/h, are placed in the silo. This mainly consists of filters, IX resins and activated core components. The silo consists of a 30 m diameter x 50 m H cylindrical concrete construction divided into shafts of different sizes for waste packages up to 2.5 m x 2.5 m. The walls of the silo are made of 0.8 m thick reinforced concrete. The space between the outer walls of the silo and the surrounding rock is backfilled with bentonite, on average 1.2 m thick. The 1 m thick concrete floor at the bottom of the silo is placed on a layer of 90/10 sand/bentonite mixture. The waste packages are placed in the shafts by overhead crane in layers. The spaces between the waste packages are gradually backfilled with porous concrete. When the silo has been filled, a 1 m thick concrete lid will cover the top, which will be covered with a thin layer of sand, a 1.5 m thick layer of sand/bentonite mixture (90/10) and the remaining space will be filled with sand, gravel or sand stabilized with cement.

The "BMA" vault, shown in Figure 12, is used for wastes with dose rates up to 100 mSv/h. This consists mainly of filters, IX resins and metallic components. The rock vault is approximately 160 m long, 19.5 m wide with a height of 16.5 m. A concrete trench has been constructed inside the vault such that it is divided into 15 separate compartments. The waste is placed in the compartments using remote handling equipment. The waste is stacked on top of the concrete floor in such a way that the waste packages act as support for prefabricated concrete cover slabs as lids for each compartment, put in position as soon as the compartments are filled. It is also possible to backfill the void between the waste packages in a compartment. Finally, a layer of concrete will be cast on top of the lid. Between the concrete structure and the rock wall there is a 2 m wide space, which will be filled with sand before closure. The space above the concrete structure may be left unfilled, but could also be backfilled. Plugs will be placed in the two entrances to the vault when the disposal facility is closed. Approximately 39,000 m^3 has been disposed in SFR as of December 2016.

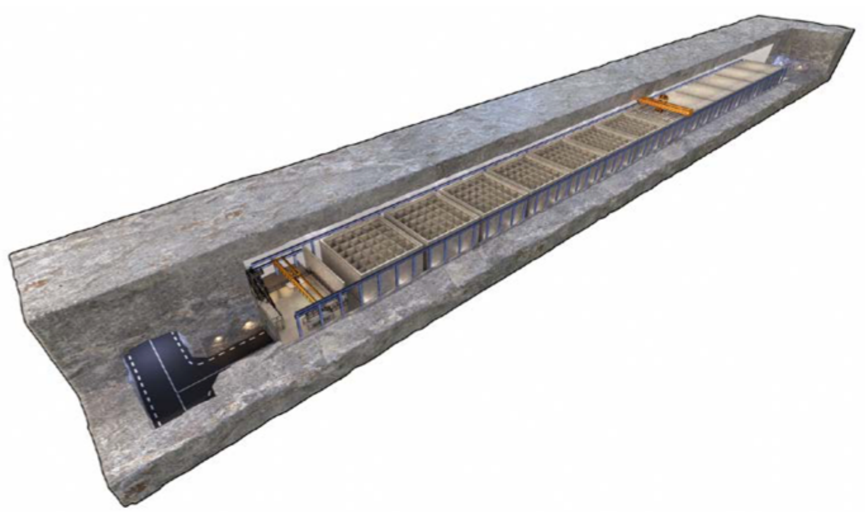

FIGURE 12: BMA Vault at SFR Repository [SKB 2020]

There are two "BTF" vaults designed for concrete tanks containing IX resins and filters with dose rates up to 10 mSv/h. The vaults are approximately 160 m L x 15 m W x 9.5 m H. The wastes are packaged in 10 m^3 standard concrete tanks which are stacked in two levels with four tanks in each row. This gives a total capacity of about 800 concrete tanks in the two vaults. A concrete radiation protection lid is placed on top of the stack. The space between the different tanks is backfilled with concrete, and the space between the tanks and the rock wall will be filled with, for example, sand and cement mixture. In addition, some large metallic components (such as steam separators or reactor vessel lids) may also be disposed of in these vaults.

The "BLA" cavern is approximately 160 m L x 15 m W x 12.5 m H. The cavern is very simple in design, with only a concrete floor on which containers are placed by forklift. During the operational phase a protective roof has been placed above the waste in order to minimize water dripping onto the waste. This inner roof will be dismantled before the disposal facility is closed.

The waste in BLA is mainly low-level scrap metal (such as iron/steel, aluminum); cellulose (such as wood, textile, paper), other organic materials (such as plastics, cables) and other waste such as insulation (such as rock wool) packed in standard steel containers. Most of the waste is in ISO freight containers, stacked three high (up to six high for half-height containers) in rows of two. In this configuration, the vault has capacity for 310 full height, 20' ISO containers. Some of the waste inside the ISO containers is also packaged in steel drums or other containers.

The maximum dose rate permitted on the surface of the waste packages is 2 mSv/h. No backfilling is planned for closure of the BLA vault.

Finland currently has two rock cavern repositories for short-lived L&ILW, one located at each nuclear power plant site. They are owned and operated by the nuclear utilities for their own wastes, with a small amount of space reserved for non-utility wastes. Both repositories are excavated in the crystalline bedrock at the nuclear power plant site, and are accessed via ramps (approximately 1 km long) for waste transport. A shaft with elevator access is provided for personnel only.

At Loviisa, the construction of the repository was started in 1993 and the operation of the first phase of the disposal facility was started in 1998. As shown in Figure 13, the Loviisa repository is located at a depth of approximately 110 m in granite bedrock. The repository consists of tunnels for solid LLW ("maintenance waste") and a cavern for solidified ILW. The maintenance waste tunnels have dimensions of 6 m W x 5 m H x 110 m long and have a waste capacity of 1,200 m^3 (or 6,000 drums). The tunnel has a concrete floor and shotcrete walls with provisions for wall drainage. The waste drums are stacked five layers high within the tunnel. The LLW tunnels are not backfilled. The reported inventory at Loviisa to end of 2016 was 1,886 m^3 of LLW [FINLAND 2017].

Inside the ILW cavern (Figure 14), the waste packages are emplaced in a trench-type structure made of reinforced concrete (approximately 70 m L x 14 m W x 11 m H). The vault will accommodate about 5,000 cylindrical concrete ILW containers (1 m^3 each internal volume, 1.7 m^3 external volume), stacked in 5 layers. The space between containers will be backfilled with concrete as each layer is filled, and will be capped with concrete once filled. The space above the capped trench will be filled with crushed rock.

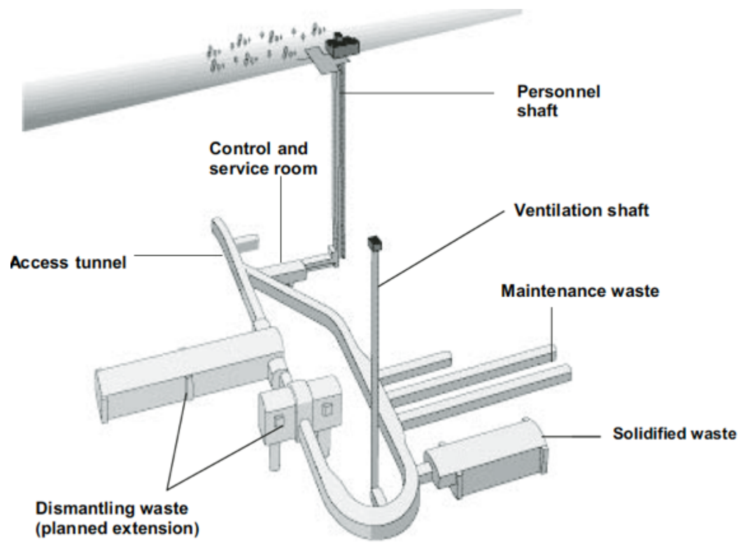

FIGURE 13: Schematic of Loviisa Repository for L&ILW [AIKAS 2008]

FIGURE 14: Loviisa ILW Cavern [NUMMI 2019]

The VLJ repository at the Olkiluoto site is of a different design. Construction began in 1988 and operation began in 1992. The repository consists of two large silos (approximately 24 m ID x 34 m H) at a depth of 60 to 95 m in tonalite bedrock, one for solid LLW and the other for bituminized ILW. The silo for solid LLW is a shotcreted rock silo, while the silo for bituminized waste consists of a thick-walled concrete silo inside a rock silo where concrete boxes containing drums of bituminized waste are stacked. The repository is shown schematically in Figure 15. At closure, the void space above the silos will be backfilled with local origin crushed rock. The reported inventory at VLJ was 5,681 m^3 of L&ILW at the end of 2016 [FINLAND 2017].

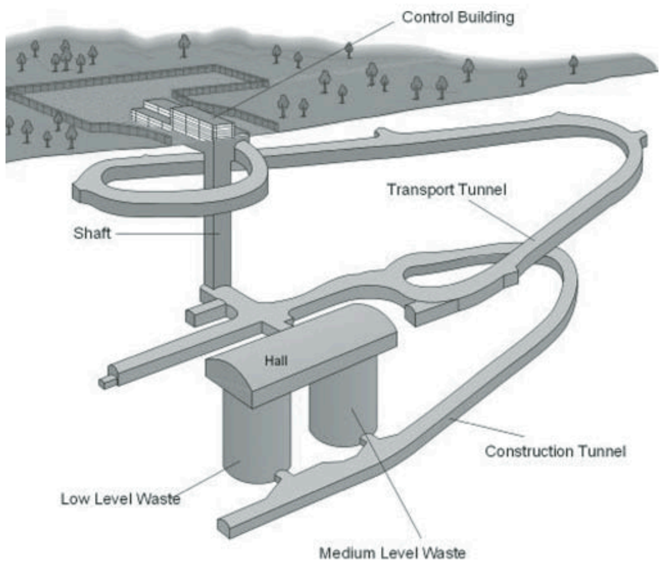

FIGURE 15: Schematic of the Olkiluoto VLJ Repository for L&ILW [AIKAS 2008]

The L&ILW from the new Olkiluoto 3 reactor will be disposed of in the same repository. The repository will be extended in the future with additional silos of similar design, to be able to receive all the waste from Olkiluoto 1, 2 and 3 reactors during the planned 60 years of operation of the units as well as for decommissioning waste.

A shallow rock cavern repository is also used in Norway at Himdalen. A unique feature of the facility is that it is a combined disposal (LLW) and storage (ILW) site. The facility, which is owned by the Norwegian State and operated by the IFE, began operation in 1999 and consists of four rock caverns built into a hillside in crystalline bedrock (gneiss) with two concrete vaults in each cavern. The total capacity of the facility is 2000 m3 (approximately 10,000 x 210-litre drums). It has a slightly inclined 150-metre long access tunnel for vehicles and personnel. All the caverns and the access tunnel have a monitored water drainage system. A service and control room for personnel and a visitor's room are located along the tunnel. As of the end of 2016, it contains approximately 36 m^3 (166 drums).

The rock caverns at Himdalen are excavated so that at least 40 metres of rock covering remains above the caverns. This natural geological covering is for physical protection against intruders, plane crashes and other similar events. It is not intended to act as a main barrier in long-term safety calculations. Long-term safety relies on the engineered barriers. In each cavern, vaults (sarcophagi) have been constructed with a concrete floor and walls. When a section of the vault has been filled, a concrete roof is constructed, shaped to shed infiltrating ground water, and a waterproof membrane will be affixed to the concrete roof. Three caverns will be used for waste disposal, with drums and containers stacked in four layers. When one layer in a vault section has been filled with waste packages, it will be backfilled with concrete.

The facility also includes a storage area for drums containing small amounts of plutonium. The storage part of the facility has the same design as the disposal part, and is situated in one of the vaults in cavern number 1. Everything placed in the storage part will be in a disposal-ready form. After the final decision regarding disposal or not with respect to these drums is taken, the waste packages will either be removed or encased in concrete in the vaults.

3.4.2 Deep rock caverns

Purpose-built deep rock cavern repositories for L&ILW are currently operated in Hungary, South Korea and the USA. They are also planned for France and Switzerland. Germany has several converted mine type deep rock cavern repositories (now closed) and is constructing a new one at Konrad. Converted mines have also been used in Czech Republic and Romania among other places.

The Waste Isolation Pilot Plan (WIPP), near Carlsbad, NM, is currently the world's only operating deep geologic repository for long-lived waste. DOE operates the facility for the disposal of transuranic (TRU) waste generated by defense related activities. Shown in Figure 16, WIPP has been operating since 1999 and currently contains about 88,000 m^3 of contact-handled (called "CH" at WIPP) and 2,400 m^3 of remote-handled (called "RH") waste. The facility is constructed at a depth of approximately 655 m in a salt formation and has a total design capacity of some 175,000 m^3 (168,000 m^3 CH and 7,000 m^3 RH). There are eight panels of 7 disposal rooms, each 91 m L x 10 m W x 4 m H. Pillars between rooms are about 30 m thick and between panels they are about 61 m thick. In addition to the eight panels, the main north-south and east-west access drifts in the panel regions are available for waste disposal and are included in the safety assessment as panels 9 and 10. There is space to construct additional panels if required.

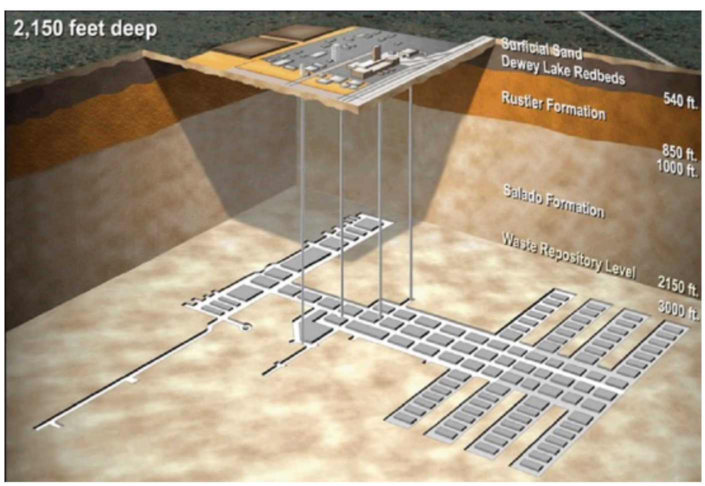

FIGURE 16: Schematic of the Waste Isolation Pilot Plant (WIPP) [SANDIA 2016]

Lower activity ("CH") TRU is stacked in the disposal rooms. Higher activity waste ("RH") is placed in horizontal boreholes drilled into the sides of the disposal rooms prior to emplacement of the contact handled waste.

Because the salt formation naturally "creeps", the disposal rooms are excavated "just-in-time". They are only left open for a few years. Sacks of magnesium oxide (MgO) are placed over the stacks of waste containers to absorb any potential carbon dioxide generation caused by the degradation of cellulosic, plastic and rubber materials in the wastes. After the rooms have been filled with waste, they are closed off. They are not backfilled. Over time, the salt will flow into the void spaces and surround the waste.

The WIPP Facility was shut down for several years from February 2014 to early 2017 following an underground fire in a salt hauling truck, followed a few days later by a contamination incident in a disposal room resulting from a burst waste package that had undergone an exothermic chemical reaction. After an extensive decontamination effort, the facility resumed operation in early 2017. Several disposal panels have been closed due to contamination or stability issues and a new ventilation system is being designed and constructed. Due to the lack of rock maintenance over the shutdown period, the ceiling in several disposal vaults collapsed. These panels are now no longer used and are being closed off.

A new underground repository for short-lived L&ILW opened in December 2012 at the Bátaapáti site in south central Hungary. The repository consists of horizontal emplacement rooms in granite host rock at a depth of approximately 250 m from the surface, with ramp access. Two access tunnels are used to provide flow-through ventilation in the main tunnel. Two disposal rooms have been constructed using controlled drill and blast, with additional disposal rooms added as required in the future. Disposal rooms are nominally 10.6 m W x 8.7 m H x 100 m long. A total of 17 disposal rooms is envisaged, giving space for up to 125,000 drums (25,000 m^3 of waste prior to packaging for disposal). Closure is planned for around 2084.

The wastes, mostly in 200 L steel drums, are grouted into 2.25 m x 2.25 m x 1.55 m H concrete containers. As shown in Figure 17, these containers are stacked in the disposal rooms, typically 4 containers wide by 4 high, with an additional top layer of 2 to 3 containers wide to fit the arched profile of disposal rooms for a total of up to 817 disposal containers (7353 x 200 L drums, or 1470 m^3 of waste). The disposal rooms will be backfilled with grout. Access tunnels will be closed with a series of concrete plugs at intervals along the length with engineered granular backfill material between each plug. The reported inventory was approximately 900 m^3 as of the end of 2016.

FIGURE 17: Disposal Vault at the Bátaapáti Repository, Hungary [NOS 2014]

A deep rock cavern silo type repository for L&ILW in granodiorite plutonic rock has been constructed in the Wolsung area of South Korea at a depth of 150 to 200 m below ground surface. The facility has been in operation since 2014. Shown schematically in Figure 18, the first phase of the repository consists of six silos, each with a capacity of 16,000 drums, for a total of about 20,000 m^3. The facility is designed for L&ILW which, under the Korean classification system, makes no distinction between short-lived and long-lived beta-gamma nuclides. However, there is a restriction on a maximum heat production of 2 kW/m^3. All wastes (mostly in 200 L drums) are placed in concrete disposal containers prior to stacking in the silos. The silos are backfilled with grout as layers of packages are stacked. As of December 2016, the facility contained about 1400 m^3 of waste.

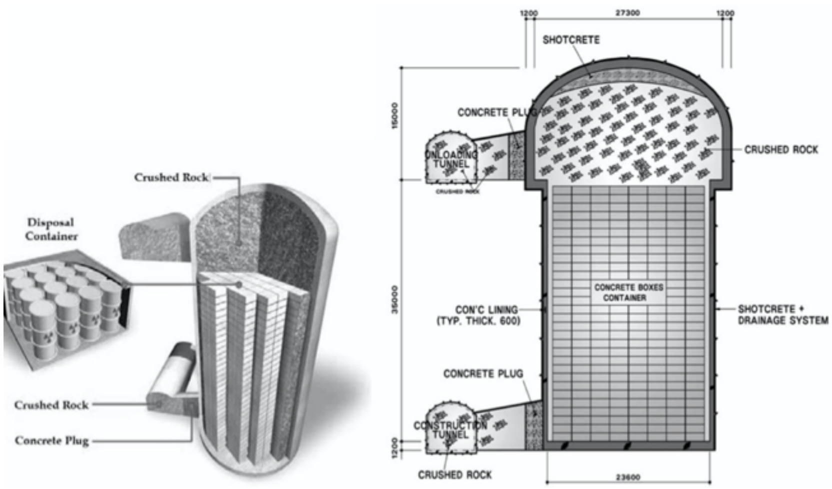

FIGURE 18: Schematic of the Wolsung L&ILW Disposal Center Phase 1 [PARK 2009]

There are several existing examples of converted mine type deep rock cavern disposal facilities. For example, ERAM Morsleben was constructed in a former salt mine in Germany. It operated from 1971 to 1998, and currently holds about 37,000 m^3 of waste, mostly in stacked 200 L to 570 L steel drums and cylindrical concrete containers in large vaults, as shown in Figure 19. The current reference plan for Morsleben is to backfill the facility with a specially formulated “salt concrete” to stabilize it. Some void space will be left open to allow volume for gas generation from waste decomposition.

FIGURE 19: Waste Emplacement at ERAM Morsleben [KERND 2020]

One of the issues with using old mine workings as repositories is that the various tunnels are often not very well mapped. In addition, some parts of the mine may be in poor physical condition, leading to structural failures in the repository zone. A prime example of this is the ASSE II former salt mine in Germany. Asse II operated as a repository from 1967 to 1978 and holds approximately 47,000 m^3 of L&ILW. The waste is distributed over eleven disposal rooms at the 750 m level, one room at the 725 m level, and one room at the 511 m level. Most of the LLW is stacked in an orderly fashion in drums laid horizontally in several layers. Some of the higher activity waste was placed in "disorganized" piles using remotely operated equipment. This was done intentionally to allow quick placement and limit radiation exposure to workers.

Due to the structural instability of the mine caused by in-leakage of water into some of the peripheral areas of the mine (which do not contain waste), the current reference plan for Asse II is to retrieve all of the waste and repackage it for disposal in another facility. The water is currently leaking in at a rate of approximately 11 m^3/day. It is highly saline, but not radioactively contaminated. After monitoring to confirm no radioactivity, it is released to another local mine for *in situ* disposal.

3.5 Borehole

Boreholes have been used for radioactive waste disposal in a few countries. In its simplest form, a borehole is a vertical shaft that is bored to a suitable diameter and depth, filled with waste, then backfilled with a cement grout or other material. The main advantage of boreholes is that they are easy to construct and operate, especially shallow near-surface boreholes. The main disadvantage for deeper boreholes is that they are limited to relatively small diameters (a few tens of centimetres in diameter), due to limitations of current deep drilling technology. The need in some cases to line boreholes (for example, with a steel casing) leads to a further reduction in usable diameter. Shallow boreholes (less than bout 30 m deep) can be constructed in a diameter size of up to several metres using existing construction drilling technology.

Shallow near-surface boreholes are typically used for spent sealed source disposal, while deeper boreholes have only been used for liquid waste disposal to date (in Russia [IAEA 2020a] and USA [STOW 1986]). Shallow boreholes have also been used in the US for the disposal of a small amount of TRU waste (~200 m^3) at a DOE facility in Nevada [USDOE 2017]. These boreholes, termed "Greater Confinement Disposal Boreholes" are typically about 3 m diameter and about 36 m deep with the lower 15 m containing the waste and the upper 21 m backfilled with screened alluvium, similar to the surrounding geological medium.

Deep borehole disposal of liquid radioactive waste involves injecting liquid wastes under pressure into porous rock layers deep underground, either as a liquid or mixed in a cement grout. The porous layers are generally surrounded by low permeability layers. There are a number of sites throughout Russia that have or currently use the injection method, such as those in Seversk and Zheleznogorsk [IAEA 2020a]. The boreholes typically range from 150 to 500 m deep, with a few going much deeper (several km). The disposal is permanent with no intent to treat the waste further or remove it in the future. The general disadvantage of this method is that permeable layers hosting the injected liquid may not be fully mapped and/or enclosed by low permeability zones. Therefore, there is a possibility that the radioactive liquid may migrate away from the injection site into aquifers used for agricultural, residential or industrial water supplies [USDOE 2011].

Deep borehole injection has also been used at the Oak Ridge National Laboratory to dispose of low-level liquid waste. The process consists of mixing liquid waste with cement and other additives that is injected under pressure through a cased well into a low-permeability shale at a depth of 300 m. The grout mixture spreads from the injection well along bedding plane fractures and solidifies in place. Each 2-day injection campaign resulted in the emplacement of approximately 750 m^3 of grout mixture. The cavity into which wastes were injected is created by hydraulically fracturing the host formation along bedding planes by the pressure of the grout [STOW 1986].

Internationally, there are very few existing examples of largescale use of boreholes for solid radioactive waste disposal, especially deep boreholes. However, the IAEA is promoting the use of near-surface and medium depth boreholes for spent sealed source disposal in countries that do not have access to any other suitable disposal methods [IAEA 2011], as shown in Figure 20 [NOS 2014].

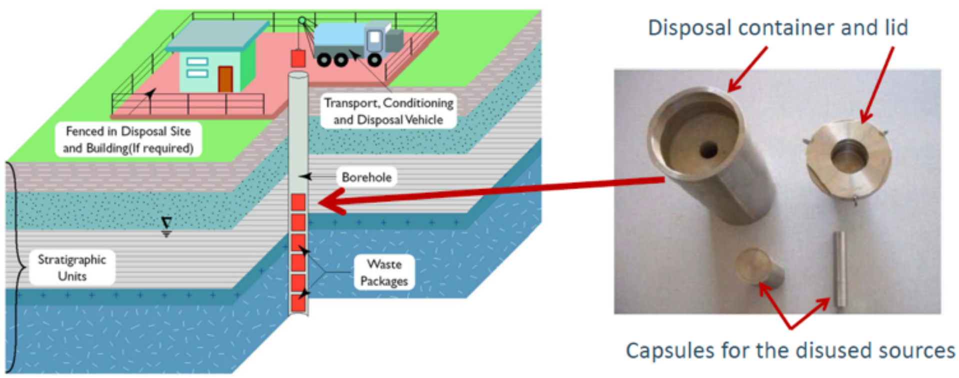

FIGURE 20: IAEA BOSS borehole disposal concept [NOS 2014]b

Deeper boreholes have been proposed and studied for solid HLW and ILW disposal in the USA, but as yet have not been deployed for this purpose.

Figure 21 shows a typical borehole design that was considered for ILW (termed GTCC – Greater than Class C in the US classification system) disposal in the USA. An array of 930 boreholes, 2.4 m diameter and 40 m deep covering an area of 44 ha was required to dispose of approximately 12,000 m^3 of GTCC waste (approximately 13 m^3 per borehole). Clean fill from borehole construction would be used to backfill the borehole above the concrete layer. Each borehole could be capped with a cover system consisting of a geotextile membrane overlain by gravel, sand, and topsoil layers [USDOE 2016]. The borehole disposal method was one of several options studied for this class of waste.

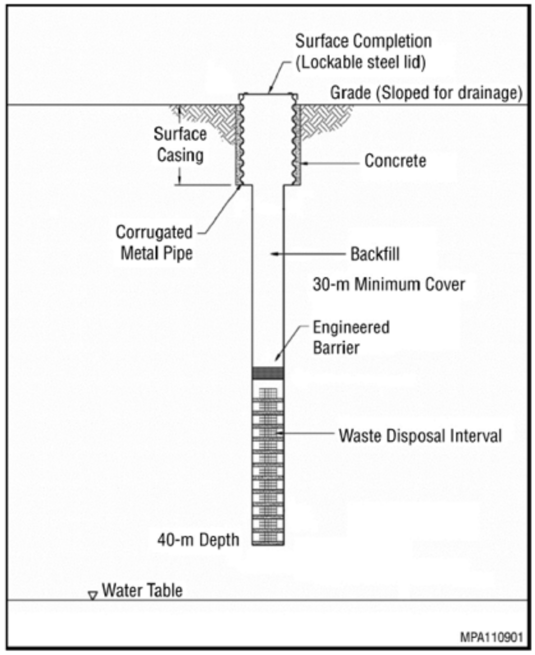

FIGURE 21: USA ILW borehole disposal concept [USDOE 2016]

3.6 Summary of disposal concepts

The main features of the various disposal concepts discussed above are summarized in Table 1. Further details about some of the examples can be found in Appendix F.

TABLE 1: Summary of disposal concepts

Concept	Typical waste types	International examples	Key features
Trench (Near-surface)	VLLW, LLW	CIRES, France (VLLW) El Cabril, Spain (VLLW) Japan (various sites, VLLW) Ezeiza, Argentina (LLW) Valpuuts, South Africa (LLW) Drigg, UK (LLW) USA (various sites, LLW)	- Easy to construct and operate, inexpensive, scalable, modular - Can be lined or unlined - Able to handle wide range of waste package sizes and masses, including unpackaged waste - Waste packages can degrade quickly, depending on the environment - Susceptible to subsidence in longer term - Not generally suitable for ILW
Aboveground mound	VLLW, LLW	Sweden (most nuclear sites, VLLW) CSM, France (LLW) Fernald Ohio, USA	- Easy to construct and operate, inexpensive - Able to handle wide range of waste package sizes and masses, including unpackaged waste - Generally suited for large volumes of waste - Waste packages can degrade quickly, depending on the environment - Generally keeps wastes above water-table - Susceptible to subsidence in longer term - Not generally suitable for ILW
Surface concrete vault	LLW	CSA, France El Cabril, Spain Drigg, UK	- Easy to construct and operate, modular and scalable - Able to handle wide range of waste package sizes and masses - Generally keeps wastes above water-table - Wide international experience - Not generally suitable for ILW
Shallow near-surface concrete vault	LLW	NRWR Mochovce, Slovakia Dukovany, Czech Republic	- Easy to construct and operate, modular and scalable - Able to handle wide range of waste package sizes and masses - Wide international experience - Can be designed for limited amounts of ILW

Concept	Typical waste types	International examples	Key features
Deeper near-surface concrete vault	LLW, ILW	Rokkasho-mura, Japan Dounreay, Scotland	- Easy operate, modular and scalable - Able to handle wide range of waste package sizes and masses - More intrusion resistant than surface or shallow vaults - Can be designed for some ILW
Shallow rock cavern	LLW	SFR, Sweden VLJ, Finland Loviisa, Finland Himdalen. Norway	- Requires large initial investment to establish surface infrastructure (for example, access ramps, hoists, shafts, ventilation, etc.) - Can be constructed in wide range of geological media - Construction and operation may be complicated by need to consider mining regulations - Waste package size and mass limited by access capacity (for example, tunnel dimensions, hoist capacity, etc.) - More intrusion resistant than surface or shallow vaults - International experience - Can be designed for some ILW
Deep rock cavern	LLW, ILW	*Purpose built:* WIPP, USA Püspökszilágy, Hungary Wolsung, South Korea *Converted mine:* Asse II, Germany ERAM Morsleben, Germany Konrad, Germany (under construction) Richard, Czech Republic Baita Bihor, Romania	- Requires large initial investment to establish surface infrastructure (for example, access ramps, hoists, shafts, ventilation, etc.) - Can be constructed in wide range of geological media - Construction and operation may be complicated by need to consider mining regulations - Waste package size and mass limited by access capacity (for example, tunnel dimensions, hoist capacity, etc.) - Intrusion resistant - International experience - Can be designed for ILW - Converted mines can harbour unknown stability issues

Concept	Typical waste types	International examples	Key features
Shallow near-surface Borehole	Sealed sources, low volume LLW	IAEA BOSS concept USDOE Facility, Nevada	- Easy to construct and operate, modular and scalable - Waste package size limited by borehole diameter - More intrusion resistant than surface or shallow vaults - Limited international experience - Can be designed for some ILW
Deep borehole	Liquid LLW and ILW	Seversk and Zheleznogorsk, Russia Oak Ridge, USA	- Modular and scalable - Waste package size severely limited by small usable borehole diameter - Geosphere difficult to characterize at depth due to limited accessibility - More intrusion resistant than shallow boreholes - International operating experience for liquid wastes, no experience for solid wastes - Can be designed for ILW and HLW

4 Implementing models

There are a number of ways that long-term radioactive waste management can be organized and operated in a country. There is no universal model that can be applied to every country [IAEA 2018]. The selection of a particular implementing model is influenced by the regulatory regime, government policy, available infrastructure, historical practices and societal preferences in a given country.

As summarized in Appendix C, many countries have opted for a centralized or “national repository” approach to disposal of LLW and ILW. These include some of the major nuclear power countries, such as France, Japan, Germany, Spain, Switzerland and UK, as well as countries with smaller nuclear programs, such as Argentina, Belgium, Czech Republic, Hungary and Romania. Within this group, some countries (for example, France, Japan, Spain and UK) have opted for separate disposal facilities for different categories of waste, while others (for example, Germany and Switzerland) have opted for co-disposing multiple classes of waste in the same facility (usually a deep geologic facility). Co-disposal has the advantages of minimizing the number of disposal facilities and reducing the need to artificially separating wastes into LLW and ILW categories. Many other countries (mainly those currently operating near-surface disposal facilities for LLW) plan to co-dispose long-lived ILW in a future repository for HLW and/or used fuel [IAEA 2018].

Other countries (for example, USA, Russia, China and Finland) have adopted a regional approach where there may be multiple facilities located in different areas of the country for one or more categories of waste, or a mixed approach which has regional repositories for some classes of waste and a national repository for others (for example Sweden, which has VLLW disposal at most nuclear sites and centralized disposal of LILW at SFR).

The various choices described above can be made for a number of reasons, such as size of waste inventory, societal preferences about number, location and type of disposal facilities; transportation issues; physical security; national policies; limited options for siting and availability of technically suitable sites; cost minimization; and general societal issues such as regional employment, infrastructure availability, etc.

In many countries, a national agency has been created with the specific responsibility for disposal of radioactive wastes. The responsibilities of the agency vary by country and may include disposal of different classes of waste, pre-disposal management, and/or decommissioning of reactors and other nuclear installations. A summary of the practices in a number of countries is given in Appendix D.

Many of the waste management agencies are government owned or controlled, such as ONDRAF/NIRAS in Belgium, ANDRA in France, BGE in Germany, PURAM in Hungary, ENRESA in Spain, and NDA in the UK. Others, such as SKB in Sweden and NAGRA in Switzerland, are primarily owned by the waste owners (mainly nuclear utilities). Another model used in a few countries is for individual waste owners to implement their own disposal for L&ILW, such as the nuclear utilities in Finland. Some countries, such as Japan and USA, operate LLW disposal as a commercial service, while higher activity wastes are the responsibility of a government agency (for example, NUMO in Japan, DOE in the USA).

5 Summary of international experience

As described in the previous sections of this paper, there is a wide variety of disposal concepts and implementing models currently used in different countries around the world for LLW and ILW. Some specific highlights are summarized below.

- In **Finland**, each nuclear power plant operator is responsible for the disposal of its own waste and there is an L&ILW disposal facility at each nuclear plant site. Both of the repositories can be classified as shallow rock cavern types, although their designs are somewhat different. A waste management organization (POSIVA), jointly owned by the utilities, is currently constructing a separate DGR for Finland's used fuel waste. This is the first such repository under construction in the world.
- The state-owned national waste management organization in **France** (ANDRA) has surface vault, mound and trench facilities for VLLW and short-lived L&ILW and is planning a DGR for long-lived ILW and HLW from reprocessing, as well as other disposal facilities for other types of waste.
- **Germany** is phasing out its nuclear power program and will be performing decommissioning activities over the coming decades. It classifies its radioactive waste into two broad categories: "heat generating" and "negligible heat generating". The negligible heat generating category includes LLW and ILW. The state-owned national waste management organization (BGE) is currently converting an old iron ore mine at Konrad into a DGR for all of its negligible heat generating wastes with a total planned capacity of 303,000 m^3. [[It is expected to begin operation by the mid 2020s.
- **Japan** operates on a commercial basis for LLW and is planning separate facilities for each waste type, including geologic repositories for HLW and long-lived wastes. It has operating deep concrete vault facilities for some types of LLW as well as trench type disposal for VLLW. Additional facilities are under development for disposal of the large amounts of accident and cleanup related wastes from Fukushima.
- **Sweden** has a centralized shallow rock cavern repository for its L&ILW. It is operated by SKB, a waste management company owned by the nuclear utilities. In 2011, SKB submitted an application to construct a separate DGR for its used nuclear fuel.
- NAGRA, the utility owned national waste management organization in **Switzerland** is looking to site two geologic repositories, one for L&ILW and one for used nuclear fuel (however, legislation does not preclude the two repositories being located on one site).
- **UK** has surface vault and trench facilities for short-lived waste and is planning a DGR for long-lived ILW and HLW from reprocessing.
- The **USA** has multiple surface disposal facilities for LLW which are operated on a commercial basis. It also has a government owned DGR for long-lived TRU waste in operation (WIPP).

6 Applicability to the Canadian context

Under the Radioactive Waste Policy Framework, each waste owner is responsible for the lifecycle management of their waste, up to and including disposal. Unlike many other countries, there is no national agency that manages radioactive waste disposal for LLW and ILW. (Under the Nuclear Fuel

Waste Act, the Nuclear Waste Management Organization (NWMO) has the responsibility to develop and implement a solution for all used nuclear fuel in Canada).

All radioactive waste management facilities in Canada are regulated by the Canadian Nuclear Safety Commission (CNSC). The CNSC is currently developing a set of regulatory guides specifically geared to various types of radioactive waste and waste management facilities to provide clarity for future waste management plans and decisions [CNSC 2018, CNSC 2021].

As shown in Appendix A and Appendix B, Canada has a wide range of radioactive waste in storage at locations across the country. In reality, any of the technical disposal concepts described in Section 3 of this paper could be applied to LLW in Canada, subject to a full safety assessment and CNSC licensing. For ILW, the international consensus is that deep disposal is required [IAEA 2018, IAEA 2020b]. In practice, this would limit the disposal options to the deep rock cavern or deep borehole concepts.

Most of the implementing models discussed in Section 4 could also be applied in Canada under the current policy. The only exception under the current policy would be the government-owned national waste management agency model, which would require a change to the current policy assigning responsibility for radioactive waste management to the waste owners. It would also likely require specific enabling legislation to set up the federal agency.

There are already examples of close cooperation between waste owners for the management of LLW and ILW. For example, OPG provides waste management services to Bruce Power on a fee-for-service basis, and CNL provides similar services to some of the non-utility waste owners. Many of the waste owners also use commercial services for some waste management activities, such as specialized processing (for example, incineration, supercompaction and metal melting at facilities in the USA). In cases where the wastes are sent to a foreign country for processing (for example, the USA), the resulting processed waste is returned to Canada for long-term management by the original owner.

There are a number of issues for implementing an integrated waste management system in Canada such as:

- Some wastes may need to be re-characterized and re-classified under a unified classification system. This may be expensive for some waste owners.
- Some wastes may require re-packaging in order to meet the WAC for disposal, especially for a near-surface type facility.
- If co-disposal is being considered, the repository must be designed for the highest class of waste to be disposed of in it. This may increase costs for the lower classes of waste. However, a combined facility may save on infrastructure costs.
- Transportation of wastes to a central facility, or one located away from a current nuclear site, may be a limiting factor in the rate at which waste can be disposed of, and may also be a limiting factor in the requirements for packaging the wastes (the regulations for transportation of radioactive material may impose additional constraints on waste package sizes, required shielding, etc.). This is especially true for Canada, where the distances between sites where the wastes are currently stored is quite large (for example, Pt Lepreau, New Brunswick to Whiteshell, Manitoba is about 3000 km by road).

However, none of these issues are insurmountable.

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Appendices

APPENDIX A: Location of radioactive waste in Canada

Source: [NRCan 2018]

APPENDIX B: Summary of waste inventories and projections in Canada

Waste type	Category/responsible party	Dec. 2016	Projection 2019	Projection 2050	Projection 2100
LLW	Operations/OPG	83,791	94,136	141,540	147,742
	Operations/NBPower	2,586	2,336	50	50
	Operations/Hydro-Québec	1,497	1,413	619	619
	Operations/Other	16,641	2,125	N/A	N/A
	R&D/AECL	526,318	529,514	546,899	561,573
	Historic/AECL & Ontario Ministry of the Environment	1,717,424	1,717,424	1,717,424	1,717,424
	Decommissioning/OPG	0	0	9,903	171,108
	Decommissioning/NBPower	0	0	1	122
	Decommissioning/Hydro-Québec	0	0	0	15,983
	Decommissioning/Other	6,000	1,000	140,000	140,000
	Decommissioning/AECL	5,128	13,590	212,165	340,330
	Total LLW	*2,359,385*	*2,361,538*	*2,626,392*	*2,946,540*
ILW	Operations/OPG	12,041	14,489	26,458	27,441
	Operations/NBPower	158	162	193	N/A
	Operations/Hydro-Québec	347	350	350	350
	Operations/Other	13	N/A	N/A	N/A
	R&D/AECL	20,331	20,375	20,472	20,537
	Decommissioning/OPG	0	0	250	16,565
	Decommissioning/NBPower	0	0	0	11
	Decommissioning/Hydro-Québec	0	0	0	1,237
	Decommissioning/Other	0	0	0	0
	Decommissioning/AECL	265	558	10,700	17,046
	Total ILW	*33,155*	*35,934*	*58,430*	*82,824*

Source: [NRCan 2018]

APPENDIX C: Summary of international radioactive waste management practices by Country and waste type

Country	VLLW	LLW (SL)	ILW (LL)	HLW	UF
Argentina*	Planned engineered surface disposal, possibly combined with LLW.	Strategic Plan reference case is "monolithic near-surface repository" for wastes requiring <300 year isolation. Former trench disposal at Ezeiza.	Strategic Plan reference case is "deep geologic repository" for wastes requiring >300 year isolation.	Included in long-lived (ILW) category.	No decision. For nuclear power plant UF, possibilities include deep disposal (by 2060) and reprocessing. Decision to be made by 2030. For research reactor fuel, policy is to return to country of origin if possible or manage with nuclear power plant fuel otherwise.
Australia	Waste below exemption limits can be free released, otherwise included as LLW.	All federally owned wastes are currently stored. Individual states are responsible for their own wastes. Some states have surface type repositories for small volumes. National policy for long-term management currently under review.	All wastes currently stored. National policy for long-term management currently under review.	All wastes currently stored. National policy for long-term management currently under review.	Research reactor fuel only. Policy is to return fuel to country of origin.

Country	VLLW	LLW (SL)	ILW (LL)	HLW	UF
Belgium	(included in LLW category)	Currently stored at central facility. Planned concrete vault type surface disposal (at Dessel).	Currently stored at central facility. No formal decision yet. Reference planning case is deep disposal in "poorly indurated clay formation" (Boom Clay or Ypresian Clay), co-located with HLW & UF.	Currently stored at central facility. No formal decision yet. Reference planning case is deep disposal in "poorly indurated clay formation" (Boom Clay or Ypresian Clay), co-located with ILW-LL & UF	Some reprocessed but moratorium on further reprocessing until long term policy developed. Reference planning case is deep disposal in "poorly indurated clay formation" (Boom Clay or Ypresian Clay), co-located with ILW-LL & HLW.
Canada*	Mainly managed as part of LLW. Some surface repositories in planning stage (for example, Chalk River Labs).	Existing storage by each major waste owner. Aboveground mound type disposal under regulatory approvals for CRL.	Existing storage by each major waste owner. Disposal options under review.	Reference case is deep disposal. Site not yet determined.	Planned deep disposal at a volunteer host site in either crystalline or sedimentary rock. Several volunteer sites under investigation.
China*	Policy is storage for decay, then free release.	Existing and planned regional near-surface repositories (trench and concrete vault types).	For alpha bearing wastes, planned deep disposal co-located with HLW.	Planned deep disposal at a centralized facility	Policy is for reprocessing of LWR UF. Research reactor & CANDU UF, planned deep disposal co-located with HLW.

Country	VLLW	LLW (SL)	ILW (LL)	HLW	UF
Czech Republic	N/A	Existing surface disposal (at Dukovany power plant site). Existing underground cavern disposal (at Bratrství for NORM waste and at Richard for institutional wastes).	Reference case is deep disposal, co-located with HLW & UF.	Reference case is deep disposal, co-located with UF & ILW-LL.	Reference case is deep disposal (~2065), co-located with ILW-LL & HLW. However, other options (for example, re-processing and regional international repository) have not been excluded.
Finland	Clearance for re-use, recycle or disposal in land fill.	Existing underground cavern disposal (at each reactor site).	Planned disposal with decommissioning wastes in extension of existing L&ILW repositories.	N/A	Deep repository at Olkiluoto currently under construction, operation starting in mid ~2020s.
France	Existing engineered trench type surface disposal (at Morvilliers).	Existing concrete vault type surface disposal (at Centre de l'Aube). Former surface disposal at La Manche.	For ILW LL - options currently under study. Reference assumption is deep disposal, possibly co-located with HLW. For LLW LL (for example, graphite) – reference assumption is dedicated near-surface repository.	Reference plan is deep disposal (licence application for CIGEO DGR at Bure in progress).	Policy is for reprocessing of nuclear power plant and most research reactor UF. Remaining research reactor fuels – reference plan is for deep disposal, possibly co-located with HLW.

Country	VLLW	LLW (SL)	ILW (LL)	HLW	UF
Germany	Clearance for re-use, recycle or disposal in land fill.	Planned deep disposal for "non-heat generating wastes" (at Konrad) under construction. Former deep repositories at Asse and Morsleben.	Planned deep disposal for "non-heat generating wastes" (at Konrad). Former deep repositories at Asse and Morsleben.	Planned deep disposal for "heat generating wastes" ~2064, site selection under way.	Included in planned deep disposal for "heat generating wastes". For research reactor fuels, return to country of origin, or manage with nuclear power plant fuel.
Hungary	N/A	Existing concrete vault and shallow borehole type near-surface repository for institutional wastes at Püspökszilágy (now full). New deep rock cavern repository at Bátaapáti commissioned in 2012.	Currently stored at site of origin. Financial reference plan for national repository for ILW-LL, HLW & UF.	Financial reference plan for national repository for ILW-LL, HLW & UF.	Financial reference plan for national repository for ILW-LL, HLW & UF. No decision on reprocessing vs disposal taken yet.
Japan	Existing demonstration surface disposal (at Tokai). Facility at Tomioka for Fukushima-related wastes. Other surface facilities planned.	Existing underground concrete vault disposal (at Rokkasho).	Planned deep, possibly co-located with HLW (effects of interactions with HLW currently under study).	Planned deep. Siting process under way.	Policy is for reprocessing of UF. Current policy under review in light of Fukushima accident.

Country	VLLW	LLW (SL)	ILW (LL)	HLW	UF
South Korea*	N/A	Existing rock cavern facility at Wolsong. Second phase consisting of near-surface vaults planned.	Planned combined disposal with HLW & UF.	Planned deep disposal for nuclear power plant UF and HLW, site not yet decided.	Planned deep disposal for nuclear power plant UF and HLW, site not yet decided. Reprocessing option still open.
Netherlands	Storage (at COVRA) followed by future free release.	Existing 100-year storage (at COVRA), followed by planned deep disposal for all waste types in a single facility.	Existing 100-year storage (at COVRA), followed by planned deep disposal for all waste types in a single facility.	Existing 100-year storage (at COVRA), followed by planned deep disposal for all waste types in a single facility.	Reprocessing until 2015, then future decision for remaining fuel. Existing 100-year storage (at COVRA), followed by planned deep disposal for all waste types in a single facility.
Romania*	N/A	Institutional wastes – existing rock cavern (former uranium mine at Baita-Bihor) nuclear power plant wastes – reference plan is for a concrete vault type near-surface repository at Saligny.	Planned deep, possibly co-located with HLW & UF.	Planned deep, possibly co-located with ILW-LL & UF.	Reference case is deep geologic disposal. Various geologic formations being investigated.

Country	VLLW	LLW (SL)	ILW (LL)	HLW	UF
Slovakia	N/A	Existing concrete vault type surface disposal at Mochovce.	Planned deep disposal, combined with HLW.	Planned deep disposal, combined with ILW-LL.	Policy is interim storage for 40 to 50 years, followed by deep disposal. Other options, such as multi-national regional repository are also being considered.
Slovenia	N/A	Planned underground concete silo type disposal adjacent to Krško nuclear power plant.	No decision.	No decision.	For nuclear power plant UF, reference plan is storage until ~2065, followed by deep disposal in either Slovenia or Croatia. Other options, such as multi-national regional repository are also being considered. For research fuel, policy is to return to country of origin where possible, otherwise manage with nuclear power plant fuel.

Country	VLLW	LLW (SL)	ILW (LL)	HLW	UF
South Africa	Existing surface disposal or decay storage and free release (for example, recycle).	Existing trench disposal at Vaalputs.	No decision on disposal technology. Reference plan of medium to deep repository. May be combined with HLW in a single deep repository.	No decision on disposal technology. Reference plan of deep repository. May be combined with ILW-LL in a single deep repository.	No decision. Current policy is storage at reactor site pending outcome of government review. Possibilities include long-term surface storage, transmutation, deep disposal and reprocessing.
Spain	Existing engineered trench type disposal (at el Cabril).	Existing concrete vault type surface disposal (at el Cabril).	Medium term reference plan is centralized storage along with HLW for 50 to 100 years. No decision taken on technology for final disposal. Reference planning assumption is deep, potentially co-located with HLW & UF.	Medium term reference plan is centralized storage along with UF for 50 to 100 years. No decision taken on technology for final disposal. Reference planning assumption is deep, potentially co-located with ILW-LL & UF.	Medium term reference plan is centralized storage for 50 to 100 years. No decision taken on technology for final disposal. Reference planning assumption is deep, potentially co-located with HLW & ILW-LL.
Sweden	Existing aboveground mound type disposal (at each nuclear site).	Existing underground cavern disposal (at SFR). Expansion of SFR to handle decommissioning wastes.	Interim storage at existing BFA Simpevarp site. Planned deep disposal starting in about 2045. Site not yet selected.	N/A	Planned deep at Forsmark site. Construction licence application filed in 2011. Expected operation late 2020s.

Country	VLLW	LLW (SL)	ILW (LL)	HLW	UF
Switzerland	N/A	Planned deep disposal, possibly co-located with repository for long-lived wastes and HLW.	Planned deep, co-located with HLW & UF.	Planned deep, co-located with ILW-LL & UF.	Some reprocessed + some planned deep disposal (utilities could choose option, but as of 2006, there is currently a moratorium on reprocessing).
United Kingdom	Conventional surface land-fill facilities.	Existing surface disposal (at Drigg & Dounreay). Other facilities may be developed if required.	Current practice is “passively safe” interim storage at major nuclear sites. Reference future plan is deep disposal, co-located with HLW.	Current practice is “passively safe” interim storage at major nuclear sites. Reference future plan is deep disposal, co-located with ILW-LL. Consultations on siting process launched in 2018.	Mostly reprocessed. Decision of whether to reprocess or dispose left to waste owner, based on economics. If disposed, would be in a single co-located deep facility.

Country	VLLW	LLW (SL)	ILW (LL)	HLW	UF
United States of America	Existing commercial surface disposal (at Clive, Utah). Existing government facilities (such as Fernald, Ohio, and various Department of Energy owned sites).	Existing commercial surface disposal (at Clive UT, Hanford WA, Barnwell SC, Andrews TX).	Currently ILW-LL (called "greater than class C" or GTCC) is an orphan with no available disposal route. (Stored at various sites). Alternatives currently under study. Options include geologic repository, intermediate depth boreholes, and enhanced near-surface facilities. Defense related TRU wastes disposed at existing deep facility (at WIPP).	HLW planned deep disposal, co-located with UF.	Planned deep disposal (location currently under review).

*Note: These countries operate one or more CANDU type heavy water reactors.

Source: Based on information published in national reports for the IAEA Joint Convention and EU Waste Directive. (See [IAEA 2018].)

APPENDIX D: Summary of international waste management responsibilities

Country	Waste Management Organisation (WMO)	Responsibilities	Ownership
Argentina	CNEA	Management of radioactive waste.	State
Australia	ANSTO	Management of radioactive waste.	State
Belgium	ONDRAF/NIRAS	Development and operation of disposal facilities for all types of radioactive waste and spent fuel.	State
Canada	NWMO	Development and operation of disposal facility for spent fuel.	Utility
	Low Level Radioactive Waste Management Office (LLRWMO)	Cleanup and management of Canada's historic waste.	State/Private
	(other waste owners)	Management and disposal of their own wastes.	Utility/State/Private
China	No specified WMO		
Czech Republic	SÚRAO	Development and operation of radioactive waste and spent fuel storage and disposal facilities.	State
Finland	Posiva Oy	Development and operation of disposal facility for spent fuel. Low level waste disposal is the direct responsibility of the nuclear power plants.	Utilities
France	ANDRA	Development and operation of disposal facilities for all types of radioactive waste.	State
Germany	BGE	Development and operation of disposal facilities for all types of radioactive waste and spent fuel.	State
Hungary	PURAM	Development and operation of storage and disposal facilities for all types of radioactive waste and spent fuel and decommissioning of nuclear facilities.	State

Country	Waste Management Organisation (WMO)	Responsibilities	Ownership
Japan	NUMO	Development and operation of disposal facility for HLW. Utilities rely on a commercial service (JNFL) for LLW disposal.	State Private (Utilities & other nuclear companies)
Korea, Republic of	KORAD	Development and operation of storage and disposal facilities for all types of radioactive waste and spent fuel, and management of radioactive waste management fund.	State
Netherlands	COVRA	Management of radioactive waste.	State
Romania	ANDR	Development and operation of disposal facilities for all types of radioactive waste and spent fuel.	State
Slovakia	JAVYS	Development and operation of storage and disposal facilities for all types of radioactive waste and spent fuel, operation of centralised waste processing facilities, and decommissioning of nuclear facilities.	State
Slovenia	Agency for Radwaste Management	Development and operation of storage and disposal facilities for all types of radioactive waste and spent fuel.	State
South Africa	NRDWI	Management of radioactive waste and spent fuel.	State
Spain	ENRESA	Development and operation of storage and disposal facilities for all types of radioactive waste and spent fuel. Decommissioning of reactors.	State
Sweden	SKB	Development and operation of storage and disposal facilities for all types of radioactive waste and spent fuel.	Utilities

Country	Waste Management Organisation (WMO)	Responsibilities	Ownership
Switzerland	NAGRA	Development and operation of storage and disposal facilities for all types of radioactive waste and spent fuel.	Utilities/State
United Kingdom	NDA	Overseeing strategic management of radioactive waste and spent fuel including waste from historic operations.	State
United States of America	DOE	Development and operation of disposal facilities for all spent fuel, certain ILW (greater than class C LLW), and DOE owned or generated radioactive waste.	State
	States/Compacts	Responsible for disposal of LLW (disposal occurs at commercially operated facilities).	Commercial services

Source: [IAEA 2018]

APPENDIX E: Summary of waste classification systems

The IAEA has attempted to unify waste definitions for reporting purposes and has proposed a standard classification system in its GSG-1 standard [IAEA 2009]:

Exempt Waste (EW): Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes, (generally based on an annual dose to members of the public of less than 0.01 mSv).

Very Short-Lived Waste (VSLW): Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge. This class includes waste containing primarily radionuclides with very short half-lives often used for research and medical purposes.

Very Low-Level Waste (VLLW): Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near-surface landfill type facilities with limited regulatory control. Such landfill type facilities may also contain other hazardous waste. Typical waste in this class includes soil and rubble with low levels of activity concentration. Concentrations of longer-lived radionuclides in VLLW are generally very limited.

Low-Level Waste (LLW): Waste that is above clearance levels, but with limited amounts of long-lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near-surface facilities. This class covers a very broad range of waste. LLW may include short-lived radionuclides at higher levels of activity concentration, and also long-lived radionuclides, but only at relatively low levels of activity concentration. (Note that this is equivalent to previous definitions of LILW-SL).

Intermediate-Level Waste (ILW): Waste that, because of its content, particularly of long-lived radionuclides, requires a greater degree of containment and isolation than that provided by near-surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal. ILW may contain long-lived radionuclides, in particular, alpha-emitting radionuclides that will not decay to a level of activity concentration acceptable for near-surface disposal during the time for which institutional controls can be relied upon. Therefore, waste in this class requires disposal at greater depths, of the order of tens of metres to a few hundred metres. (Note that this is equivalent to previous definitions of LILW-LL).

High-Level Waste (HLW): Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process (for example, thermal power > 2 kW/m3) or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal of HLW. This category includes used (spent) nuclear fuel where it has been declared a waste.

The IAEA classification system is based on minimum disposal requirements based on radiological safety considerations, with increasing degree of isolation from the biosphere through the use of natural and/or engineered barriers required for higher levels and longer-lived waste.

In Canada, this basic IAEA classification scheme has been incorporated into a CSA standard N292.0 [CSA 2019] and has been endorsed by the CNSC [CNSC 2018]:

Low-level radioactive waste **(LLW)** contains material with radionuclide content above established clearance levels and exemption quantities, and generally limited amounts of long-lived activity. LLW requires isolation and containment for up to a few hundred years. LLW generally does not require significant shielding during handling and interim storage. In the Canadian classification system, LLW also includes two sub-categories:

- *Very-short-lived low-level radioactive waste* (VSLLW)* is waste that can be stored for decay for up to a few years and subsequently cleared for release. This classification includes radioactive waste containing only short half-life radionuclides, of the kind typically used for research and biomedical purposes.

- *Very-low-level radioactive waste* (VLLW) has a low hazard potential but is nevertheless above the criteria for exemption. Long-term waste management facilities for VLLW do not usually need a high degree of containment or isolation. A near-surface repository with limited regulatory control is generally suitable. Typically, VLLW includes bulk material, such as low-activity soil and rubble, decommissioning waste and some uranium-contaminated waste.

Intermediate-level radioactive waste **(ILW)** is waste that typically exhibits sufficient levels of penetrating radiation to warrant shielding during handling and interim storage. This type of radioactive waste generally requires little or no provision for heat dissipation during its handling, transportation and long-term management. However, because of its total radioactivity level, some ILW may have heat generation implications in the short term. ILW generally contains long-lived radionuclides in concentrations that require isolation and containment for periods beyond several hundred years (for example, beyond 300 to 500 years). ILW would also include alpha-bearing radioactive waste (wastes containing one or more alpha-emitting radionuclides, usually actinides) in quantities above the levels acceptable for near-surface repositories. ILW is sometimes subdivided into short-lived (ILW-SL) and long-lived (ILW-LL), depending on the quantity of long-lived radionuclides present.

High-level radioactive waste **(HLW)*** is used (irradiated) nuclear fuel that has been declared radioactive waste or waste that generates significant heat (typically more than 2 kW/m^3) via radioactive decay. In Canada, “irradiated nuclear fuel” or “used nuclear fuel” is a more accurate term than spent fuel, as discharged fuel is considered a waste material even when it is not fully spent.

Uranium mine waste rock and mill tailings **(UMM)*** are a specific type of radioactive waste generated during the mining and milling of uranium ore and the production of uranium concentrate. In addition to tailings, mining activities typically produce large quantities of mineralized and unmineralized waste rock excavated to access the ore body. The tailings and mineralized waste rock contain significant concentrations of long-lived radioactive elements, namely thorium-230 and radium-226.

** Note: VSLLW, HLW and UMM are not discussed in this paper.*

A definitive numerical boundary between the various categories of radioactive waste (primarily low- and intermediate-level) is not provided in the CSA standard, since activity limitations differ between individual radionuclides or radionuclide groups and will be dependent on both short- and long-term safety-management considerations. A contact dose rate of about 2 mSv/h has been used, in some cases, to distinguish between low-and intermediate-level radioactive waste.

Despite the CSA classification system, most existing LLW and ILW in Canada has been classified under a variety of older systems by each waste owner which were established prior to the creation of the CSA standard. The major waste owners in Canada (OPG, AECL, NB Power, and Hydro-Québec) all have their own historical classification systems with different numerical boundaries between classes based on the capabilities of their waste management and storage systems.

APPENDIX F: Summary of typical existing repositories for low- and intermediate-level radioactive wastes

Name	Loviisa
Location	Loviisa, Finland
Description	Purpose built, rock cavern repository, excavated at depth of 110 m in granite bedrock.
Capacity	LLW: 3,600 m^3 (18,000 x 200 L drums) in first phase + approx 6,400 m^3 in recent expansion. ILW: 5,000 m^3 (5,000 x 1 m^3 packages)
History	Construction started: 1993 Operation started: 1998 (for LLW), planned 2013 for ILW Expansion: started – 2010; completed – 2012 Planned closure: 2055 (end of current operating licence)
Waste types	Short-lived LLW and ILW from Loviisa nuclear power plant operation (2 units x 488 MWe(net) VVER PWRs). LLW compacted and/or packaged in 200 L steel drums. ILW (IX resins & sludges) to be cemented into cylindrical concrete containers (1 m^3 internal volume, 1.7 m^3 external volume). Eventual decommissioning waste from Loviisa reactors.
Key Features	Access via 1.1 km ramp tunnel. Personnel access via 120 m shaft with lift & stairway. Separate caverns for LLW and ILW. Disposal caverns are "dead-ended" ventilation. LLW caverns 6 m W x 5 m H x 110 m L. 200 L carbon steel drums stacked 7 wide x 5 high. LLW caverns not backfilled at closure. Internal drip shield roof used during filling to protect drums from water infiltration to be removed prior to closure. ILW cavern with internal concrete trench structure (14 m W x 11 m H x 70 m L), serviced by overhead crane. Concrete waste packages are stacked 5 high. Cavern is backfilled with concrete grout as each layer is filled. Will be capped with concrete when completed. Remaining vault space filled with crushed rock.
Comments	Reported inventory to end of 2016 was 1,886 m^3 of LLW. May also contain small amounts of decommissioning waste from other facilities (for example, research reactors).
Reference	[FINLAND 2017]

Name	VLJ Repository (Voimalaitosjätteen loppusijoitustila)
Location	Olkiluoto, Finland
Description	Purpose built, silo type rock cavern repository, excavated at depth of 60 to 95 m in tonalite bedrock.
Capacity	LLW Silo: 5,000 m^3 ILW Silo: 3,500 m^3 Total of 4 additional silos to be added as required in future.
History	Construction started: 1988 Operation started: 1992 Expansion: (planned for waste from new reactor and future decommissioning wastes) Planned closure: (after decommissioning of last reactor on site)
Waste types	Short-lived LLW and ILW from Olkiluoto nuclear power plant operation (2 units x 880 MWe(net) BWRs, 1 unit 1600 MWe EPR under construction, possible 4^{th} unit under consideration). LLW compacted and/or packaged in 200 L steel drums. ILW (IX resins & sludges) bituminized in drums, in concrete boxes. Eventual decommissioning waste from Olkiluoto reactors.
Key Features	Access via 1.1 km ramp tunnel. Personnel access via shaft with lift. Shotcreted rock silo for LLW, 24 m ID x 34 m H. Wastes packaged in 200 L drums, 1.4 m^3 steel boxes, 3.9 m^3 concrete boxes (containing 12 drums) or 5.2 m^3 concrete boxes (containing 16 drums). Thick-walled concrete silo inside a rock silo for ILW. 5.2 m^3 concrete boxes containing 16 drums of bituminized waste stacked in silo. Overhead crane hall common to both silos used to stack packages. Silos contain 31 tiers of concrete stacking boxes. Void space above silos will be backfilled with local origin crushed rock at closure.
Comments	Reported inventory to end of 2016 was 5,681 m^3 of L&ILW. Also stores small amounts of state-owned L&ILW in a dedicated cavern (~55 m^3 of L&ILW, 53 kg Th, 1270 kg DU).
Reference	[FINLAND 2017]

Name	CSM
Location	La Manche, France
Description	Purpose built, above ground mound/concrete vault repository for short-lived L&ILW.
Capacity	Total disposed volume ~527,000 m^3
History	Construction started: 1967 Operation: 1969 to 1994 Closure: capping completed in 1997. Currently under long-term monitoring for up to 300 years of institutional control.
Waste Types	Short-lived L&ILW from nuclear power plants and fuel cycle facilities in various package types.
Key Features	Waste containers stacked directly on concrete slabs or in concrete bunkers built on the slabs. Spaces between containers backfilled with sand, gravel or concrete. Multi-layer capping system with various membranes and drainage layers. Drainage monitored for radioactivity.
Comments	Occupies approximately 15 ha, adjacent to La Hague reprocessing facility. Documentation on design and inventory is stored in French National Archives. Some settlement of the cover system was observed & remediation carried out in 2009-2010. Approximately 300 m^3/year of water collected in the internal drainage system. Tritium detected in groundwater around facility.
Reference	[FRANCE 2017]

Name	CSFMA (Centre de l'Aube)
Location	Aube, France
Description	Purpose built, above ground concrete vault repository for short-lived L&ILW.
Capacity	Current licenced capacity of 1,000,000 m^3 in 400 disposal vaults.
History	Construction started: 1989 Operation started: 1992 Closure: (planned future)
Waste types	Short-lived L&ILW from nuclear power plants and fuel cycle facilities in various package types.
Key features	Wastes normally compacted and/or grouted into containers. Waste containers stacked directly in 25 m x 25 m x 8 m high concrete vaults using overhead crane. Moveable weather shelter protects open vaults during waste loading. Spaces between containers backfilled with sand, gravel or concrete. Vaults are capped with concrete. Multi-layer capping system planned with various membranes and drainage layers. Drainage collected and monitored for radioactivity.
Comments	Total volume disposed to end of 2016 ~325,000 m^3. 106 vaults filled and capped.
Reference	[FRANCE 2017]

Name	CIRES (CSTFA)
Location	Morvilliers, France
Description	Purpose built, trench facility in clay for very-low level wastes.
Capacity	650,000 m^3
History	Construction started: 2002 Operation started: 2003 Planned closure: 2033 (30-year operating licence)
Waste types	Very low-level waste from nuclear power plants and fuel cycle facilities (mostly from decommissioning activities) in bulk or simple containers, such as plastic/fabric bags. Approximately 50% of the VLLW consists of “industrial waste” (metal scrap and plastics), 40% of “inert waste” (concrete, bricks, soil, etc.) and 10% of “special waste”, which includes various substances such as sludges and ash. Average radioactive level of about 10 (Bq/g), with a range of 1 to 100 Bq/g.
Key Features	Total site area is 45 ha, of which 28.5 is available for disposal purposes. Disposal cells are excavated progressively, as needed, directly in the clay formation down to a depth of 8 m and are filled in sequence. Each of the first six cells had a capacity of 10,000 m^3. “Double” cells have been constructed since 2007 with an increased capacity of up to 25,000 m^3 (26 m wide by 174 m long). Cells are filled up in successive layers (about 10 on average) while void spaces between waste packages are incrementally backfilled with sand. The waste container has no radioactivity confinement function and is solely for facilitating handling and disposal operations, while protecting the operators. Average waste delivery rate to date is approximately 24,000 m^3/yr. Facility is designed for a 30-year operating life, followed by covering with an engineered multilayer capping system and postclosure monitoring period of 30 years.
Comments	Reported inventory to end of 2016 was approximately 330,000 m^3 of VLLW. Construction cost reported as 40 million Euros, and operational cost of 270 Euros per tonne. (French acronym for VLLW = TFA - très faible activité)
Reference	[FRANCE 2017]

Name	Asse II
Location	Wolfenbüttel, Lower Saxony, Germany
Description	Converted former potash and salt mine, with disposal rooms at 511 m, 725 m, and 750 m below ground surface, in original mine excavations.
Capacity	Currently holds approximately 47,000 m^3 of L&ILW.
History	Operated as salt and potash mine from 1908 to 1964. Mine acquired for a repository in 1965. Disposal of LLW starts in 1967, ILW in 1972. Operates as a repository until 1978.
Waste types	Non-heat generating L&ILW, mostly from operation of the Karlsruhe nuclear research centre and its experimental fuel reprocessing facility.
Key features	Shaft and hoist access. ILW disposed in room at 511 m level. LLW disposed in rooms at 725 and 750 m level. Wastes are mostly in 200 L drums. LLW is stacked in an orderly fashion, while ILW was tipped in a “disorganized pile”. Tipping from a frontend loader was intentional for the higher dose rate wastes to minimize operator exposure during handling according to ALARA procedures of the time. Emplacement rooms were not backfilled.
Comments	About 5 million m^3 of rock salt and potash minerals excavated from mine over its life. Most of this space was left open and not backfilled at the time. Two nearby mines (Asse I and Asse 3) flooded in the early part of the 20th century and were abandoned. The salt creep induced convergence and stress redistribution around the chambers creating pathways for groundwater inflow. Since 1988, there has been a fairly constant inflow of about 11 m^3/day (8 l/min) NaCl saturated brine into peripheral areas of the mine. Brine is pumped out, monitored and free-released to another salt mine facility. Current reference plan is to retrieve all waste and re-package for disposal in the new Konrad facility, currently under construction. Approximately 1.75 million m^3 of salt concrete (*salzbeton* – typically 16% cement, 39% halite, 16% limestone powder, 14% water and 15% sand) has been used to infill parts of the mine to stabilize it from further deterioration while the waste retrieval is executed. However, the salt continues to creep (about 130 mm per year) and new groundwater pathways are continually opening up.
Reference	[GERMANY 2017]

Name	ERAM (Endlager für Radioaktive Abfälle Morsleben)
Location	Morsleben, Saxony-Anhalt, Germany
Description	Converted former potash and salt mine, with disposal rooms at about 400 m to 600 m below ground surface, in original mine excavations.
Capacity	Currently holds approximately 37,000 m^3 of L&ILW.
History	Operated as salt and potash mine from 1897 to 1969. Mine acquired for a repository in 1970. Operated as an L&ILW repository from 1971 to 1998.
Waste types	L&ILW from operation and decommissioning of nuclear power plants as well as waste from research, medical and industrial application, mostly in the former East Germany.
Key features	Shaft and hoist access. Most waste in 200-L, 280-L, 400-L and 570-L steel drums and cylindrical concrete containers. Waste stacked in orderly fashion. Large emplacement rooms, up to 30 m wide x 100 m long. Low water inflow rate (~12 m^3/year). Emplacement rooms were not backfilled. However, some roof areas have partially collapsed.
Comments	The original closure plan developed in 1989 was to allow facility to flood. Reference closure plan was changed upon reunification of former East and West Germany. Current closure plan is to backfill emplacement vaults and access areas with salt concrete (*salzbeton* – typically 16% cement, 39% halite, 16% limestone powder, 14% water and 15% sand) to stabilize. Plan awaiting final approval by regulatory authorities. Some abandoned workings have been backfilled with about 935,000 m^3 of concrete to stabilize for worker and mine safety reasons. Some cavities will be left open on purpose to provide void space for gas generation from degradation of organic materials in the waste and steel containers.
Reference	[GERMANY 2017]

Name	Konrad
Location	Salzgitter, Lower Saxony, Germany
Description	Purpose-built, tunnel-type rock cavern repository using infrastructure of former iron ore mine (shafts, access tunnels, etc.) at a depth of ~800 m in Oolitic limestone.
Capacity	63,000 m^3 of non-heat generating L&ILW in first phase, with future expansions up to 303,000 m^3 planned.
History	Operated as iron-ore mine from 1965 to 1976. Final construction licence granted in 2008. Repository conversion under construction, with operation planned to start in 2022.
Waste types	Non-heat generating L&ILW from operation and decommissioning of nuclear power plants as well as waste from research, medical and industrial application.
Key features	Shaft and hoist access. Two shafts: personnel access & ventilation intake in one and waste package handling & ventilation exhaust in the other). Five large, newly constructed, emplacement rooms, 7 m W x 6 m H x 800 m L, in first phase. Emplacement rooms and access tunnels have flow-through ventilation (with some ducting in emplacement rooms). Wastes are packaged into a small number of standard container types, including steel boxes (ranging in size from ~4 m^3 to 12 m^3), cast iron casks (~1 m^3 to 1.3 m^3) and concrete containers (~1.2 m^3). The outer disposal container may contain several smaller containers inside (for example, 200 L or 400 L drums). The void space inside the containers is normally grouted. Some ILW containers have integral shielding. Waste packages are prepared off-site and designed to meet transport regulations (due to need to transport all wastes from off-site to the facility). Waste stacked in orderly fashion. Negligible water inflow rate.
Comments	Current reference is to backfill disposal vaults with a crushed rock/cement mix (~70 wt% crushed rock, 10% cement, 20% water) as they are being filled (for example, after about every 50 m of tunnel length has been filled, a wall will be constructed and the grout mix pumped into the space behind the wall). On closure, the remainder (access drifts, ventilation drifts and infrastructure rooms) will be backfilled with crushed rock (mainly from the mine excavation).
Reference	[GERMANY 2017]

Name	National Radioactive Waste Repository
Location	Bátaapáti, Hungary
Description	Purpose built, rock cavern repository, excavated at a depth of 250 m in granite bedrock, ramp access.
Capacity	Currently 2 disposal vaults to hold approximately 3,000 m^3 of short-lived L&ILW (15,000 drums). Expansion plans to 17 disposal vaults for total of 25,000 m^3 (125,000 drums).
History	Geological investigations completed in 2003 Construction licence granted: 2008 Operation started: 2012 Planned closure: 2084
Waste types	L&ILW from operation and decommissioning of nuclear power plants.
Key features	Double tunnel, ramp access to provide flow-through ventilation in main tunnels. Disposal vaults are dead-ended. Most waste in 200-L steel drums, grouted into 2.25 m x 2.25 m x 1.55 m H concrete containers, 9 drums per container. Waste stacked in vaults, typically 4 containers wide x 4 high. Emplacement rooms, nominally 10.6 m W x 8.7 m H x 100 m long, arched profile. Each holds up to 817 disposal containers. Emplacement rooms will be backfilled with grout. One disposal room will be constructed with internal concrete vault to avoid having to repackage existing containers in storage. Access tunnels will be closed with series of concrete plugs at intervals along the length with engineered backfill between plugs.
Comments	Built into hillside. Facility began operation in December 2012. Reported inventory to end of 2016 was about 900 m^3.
Reference	[HUNGARY 2017]

Name	JNFL Rokkasho-mura LLW Disposal Center
Location	Rokkasho, Japan
Description	Purpose built, in-ground concrete vault repository for short-lived L&ILW, approximately 10 m below grade to base of vaults.
Capacity	Number 1 disposal facility: 40,000 m^3 Number 2 disposal facility: 40,000 m^3 Planned expansions for both facilities up to total of 600,000 m^3 (3 million drums).
History	Construction started: 1990 Operation started: 1992 (Number 1 disposal facility); 2000 (Number 2 disposal facility) Closure: (planned future)
Waste types	Short-lived L&ILW, mostly from nuclear power plant operation. Number 1 disposal facility is for homogeneous solidified waste (for example, IX resins, concentrates, etc.). Number 2 disposal facility is for compacted and solidified wastes (for example, metals, concrete, etc.).
Key features	Concrete vaults constructed in large pits excavated 15 to 20 m below grade to bedrock. Number 1 facility vaults are 24 m x 24 m x 6 m high, subdivided into 16 cells of 6 m x 6 m, holding 320 drums (8 layers of 8 x 5 grid, stacked horizontally). Number 2 facility vaults are 36 m x 36 m x 7 m high, subdivided into 36 cells, each with 360 drums (9 layers of 8 x 5 grid, stacked horizontally). Most wastes in 200 L carbon steel drums. Automated drum handler places row of 8 drums at one time. Spaces between drums backfilled with concrete. Vaults are capped with concrete. Multi-layer capping system planned with various impermeable and drainage layers.
Comments	To end of 2016, Number 1 facility contained about 147,000 drums (~29,000 m^3) and Number 2 facility about 113,000 drums (~22,600 m^3). Intermediate depth disposal (~100 m) for higher activity LLW planned for same site, starting about 2023.
Reference	[JAPAN 2017]

Name	Wolsung L&ILW Disposal Center
Location	Wolsung, Gyeongju, Korea
Description	Purpose built, silo type rock cavern repository, excavated at depth of 150 to 200 m below ground surface in granodiorite bedrock.
Capacity	20,000 m^3 total in six silos of first phase. Expansion of up to 160,000 m^3 planned.
History	Site selected: 2006 Construction started: 2008 Operation started: 2014 Closure: (planned future)
Waste types	L&ILW with heat rate less than 2 kW/m^3. Upper concentration limits for some nuclides including H-3, C-14, Co-60, Ni-59, Ni-63, Sr-90, Nb-94, Tc-99, I-129, Cs-137 and gross alpha.
Key features	Silos are approximately 24 m ID x 35 m high. 0.6 m thick concrete lining with engineered drainage system between liner and rock. Separate silos for different waste types. Access via two ramp tunnels – one goes to top of silo for waste handling, other to bottom for construction access. Drums placed in concrete disposal containers: 16-Pack (4×4) disposal containers for 200-L drums and 9-Pack (3×3) disposal containers for 320-L drums. Disposal containers stacked in silos by overhead crane. Top hall of filled silos to be backfilled with crushed rock. Concrete plugs to be constructed in entrance tunnels at top and bottom of each silo. Interconnecting access tunnels to be backfilled with crushed rock. Main transport ramp tunnels will be closed with concrete plugs at strategic locations without systematic backfill.
Comments	As of December 2016, the facility contained about 1400 m^3 of waste. The restriction on C-14 concentration (2.22 E+5 Bq/g) would exclude CANDU moderator IX resins. Expansion with a French style near-surface disposal is under construction at the site.
Reference	[KOREA 2017]

Name	El Cabril (Almacén Centralizado de Residuos Radiactivos de Baja y Media Actividad El Cabril)
Location	Cordoba, Spain
Description	Purpose built, above ground concrete vault repository for short-lived L&ILW.
Capacity	Current capacity: 37,000 m^3 Expansion up to 90,000 m^3 foreseen.
History	Site selected: 1986 Construction started: 1990 Operation started: 1992 Closure: (planned future)
Waste types	Short-lived L&ILW
Key features	Wastes normally compacted and/or grouted into 200 L drums or 1.3 m^3 steel boxes. Drums and boxes encapsulated in 2.2 m x 2.2 m x 2.2 m concrete disposal package (11 m^3), approximately 25 tonnes gross weight per package. Steel stacking frames are also used instead of concrete boxes for some lower activity drums. Concrete disposal containers stacked directly in 24 m x 19 m x 9 m high concrete vaults using overhead crane. Moveable weather shelter protects open vaults during waste loading. Spaces between containers backfilled with gravel. Vaults are capped with concrete. Multi-layer capping system planned with various membranes and drainage layers. Drainage collected and monitored for radioactivity.
Comments	As of the end of 2016, approximately 32,000 m^3 of L&ILW was disposed of in El Cabril.
Reference	[SPAIN 2017]

Name	SFR (Slutförvaret för kortlivat radioaktivt avfall)
Location	Forsmark, Sweden
Description	Purpose-built, rock cavern and silo repository, excavated at a depth of 50 m below sea bed in granite bedrock.
Capacity	63,000 m^3, expansion for up to 200,000 m^3 planned.
History	Construction started: 1983 Operation started: 1988 Expansion: planned for 2020s Closure: (planned future)
Waste types	Short-lived L&ILW, up to 500 mSv/h dose rate on waste package.
Key features	Ramp access, approximately 1 km out from shoreline, under the Baltic sea. 4 rock caverns for different kinds of wastes. 160 m long x 15 to 19 m W x 10 to 17 m H, flow through ventilation. One of the caverns is divided up into 15 compartments with wastes placed by overhead crane. Other caverns are “drive in” with wastes emplaced by forklift. 1 concrete silo for highest activity wastes, 30 m dia x 50 m H, divided into shafts approximately 2.5 m x 2.5 m. Silo and 3 of 4 caverns to be backfilled grout and/or bentonite mixture when filled with waste. No backfill planned for cavern with lowest activity wastes. Planned expansion will have additional large caverns to be used mainly for decommissioning waste.
Comments	Approximately 39,000 m^3 disposed in SFR as of December 2016.
Reference	[SWEDEN 2017]

Name	Low Level Waste Repository
Location	Drigg, Cumbria, UK
Description	Purpose-built, near-surface repository for short-lived L&ILW, approximately 5 m below grade to base of vaults.
Capacity	800,000 m^3 in clay-lined trenches 400,000 m^3 in two concrete vaults Future expansion of further 600,000 m^3 in concrete vaults planned (1.8 million m^3 total for repository).
History	Operation started: 1959 (shallow trench burial) Operation of concrete vaults started in 1988 Closure: clay trenches – 1995. Concrete vaults – (planned future)
Waste types	Short-lived L&ILW with alpha < 4,000 Bq/g and beta-gamma <12,000 Bq/g.
Key features	The 7 clay trenches were about 750 m long x 30 m wide x 5 to 8 m deep. Clay trench use was discontinued in 1995 and are now closed. The two new concrete disposal vaults are about 180 m W x 200 m L x 5 m H, subdivided into 3 bays of 60 m wide each. Vaults are constructed on a concrete base with an engineered drainage system, slightly below grade. Most wastes currently compacted and grouted into ISO freight containers. The ISO containers are stacked 4 high for half-height containers or 2 high for full height containers, using a heavy duty forklift. Temporary weather shelters are not used during loading of wastes into vault. Rainwater during loading is collected and monitored. At closure, void space between and around containers will be backfilled with grout for structural stability and containment purposes, and the vaults capped with a multi-layer engineered capping system. 100-year monitoring and institutional control is planned post closure.
Comments	Total disposed inventory to April 2016 is reported as 1 million m^3. Average rainfall in the area is about 1200 mm.
Reference	[UK 2017]

Name	WIPP (Waste Isolation Pilot Plant)
Location	Carlsbad, NM USA
Description	Purpose built, rock cavern repository, excavated at depth of 655 m below surface in a salt bed.
Capacity	175,000 m^3 (6.2 million cubic feet)
History	Site selected: 1974 Construction started: 1981 Ready for operation: 1988 Operation started: 1999 (delay caused by various court challenges) Expansion: new disposal rooms excavated as required "just-in-time" Closure: (planned future, around 2035)
Waste types	Defense related contact handled and remote handled TRU
Key features	Four vertical shafts: Air intake, air exhaust, salt handling and waste handling. Personnel access via salt handling shaft or waste handling shaft. Emergency egress can also be done via air intake shaft. Exhaust shaft does not have a hoist. Disposal rooms are excavated in panels of 7 rooms using road headers. Each room is approximately 10 m W x 92 m L x 4 m H and each room is separated by 30 m wide pillar of undisturbed salt. Contact handled waste (< 2 mSv/h dose rate) are stacked on pallets in rooms. Remote handled waste is placed in 0.76 m ID x 5 m L boreholes drilled in the side of disposal rooms on 2.4 m centres prior to bringing in contact handled waste. Waste is also emplaced in the tunnels connecting disposal rooms. Sacks of Magnesium Oxide (MgO) are placed on top of waste stacks. It is used to provide an engineered barrier that decreases the solubility of the actinide elements in TRU waste. MgO essentially consumes carbon dioxide that would be produced by microbial consumption of cellulose, plastic, and rubber in the emplaced contact-handled (CH) waste. Waste emplacement rooms are not backfilled. Rooms are allowed to close from the natural creep of the salt formation.
Comments	As of the end of 2016, WIPP contained about 88,000 m^3 of contact handled and 2,400 m^3 of remote handled TRU waste. The facility was shutdown February 2014 to January 2017 due to an accident in February 2014 that resulted in underground contamination. Some disposal panels now unusable.
Reference	[USA 2017]

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