UDC: 621.039.7

TECHNOLOGIES OF RADIOACTIVE WASTE DISPOSAL: EUROPEAN EXPERIENCE AND TRENDS

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Article received on June 26, 2018

The paper focuses on European experience in the development and operation of disposal facilities for radioactive waste and trends in the development of disposal technologies.

Key words: *short-lived and long-lived radioactive waste, very low-level waste, high level waste, surface and near-surface disposal facilities, deep geological disposal facilities.*

Final disposal of radioactive waste (RW) was set as a task for the nuclear sector in the second half of the XX century due to active deployment of research and military nuclear programs and the global development of nuclear energy. In addressing this task several stages have been undergone allowing to accumulate huge international experience which is supposed to be of use for countries embarking on the development of national radioactive waste disposal facilities (DFRW).

To date, a unified policy on the final stage of RW management has been established globally. It is based on the principles of multi-barrier environmental protection, protection of life and health of the population, as well as the principle suggesting that no undue burden associated with RW management issues is imposed on future generations.

However, despite broad international cooperation and unified approaches being in place in the field of final RW disposal, some important differences exist when it comes to addressing relevant technical and organizational issues faced during the development of DFRW in different countries. These differences result from the specific aspects of legal framework, as well as political, social, climatic and geological factors being specific for each country.

This article provides a brief analysis of engineering solutions applied at already existing facilities for final disposal of RW, as well as those used in promising DFRW projects being under development. Such analysis enabled to identify the main trends in disposal technologies applied in Europe and associated with different RW categories.

To date, in most European countries this stage of RW management have already been implemented allowing the final disposal of very low-level waste (VLLW), short-lived low-level waste (SL-LLW) and short-lived intermediate-level waste (SL-ILW). Solutions enabling to address challenges associated with the disposal of long-lived low-level waste (LL-LLW) and long-lived intermediate-level waste (LL-ILW), as well as high-level waste (HLW) and spent nuclear fuel (SNF) are being under development.

Table 1 presents DFRWs already existing and being under development in a number of European countries operating nuclear power plants. Detailed overview of international disposal practices can be found in [1].

Table 1. Characteristics of DFRW existing or being under development in some European countries

Country	Name, operational time period	DF RW type, data on bedrock and category of disposed RW			DFRW capacity
		Surface (or shallow)	Underground (depth of up to 100 m)	Deep (depth over 100 m)	
France	CSM, 1969–1994	SL-LLW, SL-ILW	-	-	527,000 m³
France	CSA, 1992–till present time	SL-LLW, SL-ILW	-	-	1,000,000 m³
France	Cires, 2003–till present time	VLLW (8 m deep)	-	-	650,000 m³
France	No data available	-	LL-LLW, Depth not defined yet	-	180,000 m³
France	Cigeo	-	-	LL-ILW, HLW, 500 m	83,500 m³
Spain	El Cabril (Vault 1-28), 1992–till present time	SL-LLW, SL-ILW	-	-	100,000 m³
Spain	El Cabril (Vault 29-32), 2007–till present time	VLLW	-	-	130,000 m³
UK	Drigg, 1959–till present time	SL-LLW	-	-	1,000,000 m³
UK	GDF, time period is unknown	-	-	LL-LLW, LL-ILW, HLW, SNF	some 650,000 m³
Germany	ASSE II, 1967–1978	-	-	LLW, ILW, 510–750 m	some 25,000 m³
Germany	Morsleben, 1972–1998	-	-	LLW, ILW, 480 m	37,000 m³
Germany	Konrad, 2021–	-	-	LLW, ILW, 800–1,300 m	650,000 m³
Germany	Gorleben	-	-	HLW, SNF 840–1,200 m	Over 16 t of HLW, SNF (~ 9,000 packages)
Switzerland	No name given, 2050–2065	-	-	LLW, ILW, 400 m	100,000 m³
Switzerland	No name given, 2060–2075	-	-	LL-ILW, HLW, SNF, 600–800 m	317 packages of HLW, 1,894 packages of SNF
Belgium	cAt project, 2016–2031	SL-LLW, SL-ILW	-	-	30,600 packages
Belgium	No data available	-	-	LL-LLW, LL-ILW, HLW 220 m	11,100 m³ LL-LLW, LL-ILW, 600 m³ HLW
Sweden	SFR, 1988–till present time	-	SL-LLW, SL-ILW, 60 m	-	63,000 m³. Extended to over 200,000 m³
Sweden	SFL, Not earlier than 2035	-	-	LL-LLW, LL-ILW, 500 m	16,000 m³
Sweden	KBS-3	-	-	SNF, 500 m	6,000 packages
Sweden	Oskarshamn, 1986–2025	VLLW	-	-	10,000 m³
Sweden	Studsvik, 1988–2010	VLLW	-	-	1,540 m³
Sweden	Forsmark, 1989–2040	VLLW	-	-	17,000 m³
Sweden	Ringhals, 1993–2030	VLLW	-	-	10,000 m³
Finland	VLJ Olkiluoto, 1992–till present time	-	SL-LLW, SL-ILW 60–100 m	-	5,000 m³ of SL-LLW, 3,500 m³ of SL-ILW
Finland	VLJ Loviisa, 1998–till present time	-	-	SL-LLW, SL-ILW, 110 m	8,700 m³
Finland	Onkalo, 2022–2120	-	-	SNF, 450 m	5,4 t of SNF (2,800 packages)
Hungary	RWTDF, 1976–2005	SL-LLW	-	-	5,000 m³
Hungary	Bataapati, 2012–2037	-	-	SL-LLW, SL-ILW, 250 m	40,000 m³
Hungary	2064–2079	-	-	LL-LLW, LL-ILW, HLW, SNF	No data available

Legend: Clay Crystalline rocks Salts

VLLW disposal

Final disposal technology for VLLW with a potential hazard period not exceeding 100 years in most of the countries suggests the use of simplified DFRW structures such as trenches and mounds (Figures 1, 2). Safety of these structures is provided mainly by multi-layer cover and underlying screens.

Figure 1. VLLW disposal technology at the DFRW site (Oskarhamn NPP, Sweden): installation of the covering screen [2]

Figure 2. VLLW disposal technology at Cires DFRW (Morvilliers site, France) [3]

In terms of its structure, VLLW disposal facility (DF) at Oskarhamn NPP site can be viewed as an impermeable 0.5 m thick concrete base with an underlying natural moraine being 2 m thick, backfilled with a pebble and sand stone chips mixture. VLLW packages are stacked forming an elongated mound. Voids are backfilled with sand. A multi-layer cover is installed on its top including a pebble-stone chips mixture, a 0.4 m thick hydraulic bentonite barrier with fine-grained stone chippings, bentonite textiles, pebble drainage layer, geotextile material, a 1.2 m thick moraine layer. Vegetation layer is applied on the very top of the mound [2].

CIRES, centralized VLLW disposal facility in France, is a network of 8 m deep trenches excavated in near-surface clay layer with some temporary structures installed above. A covering screen featuring 2 mm thick high-density polyethylene layer, the clay material excavated during trench construction (from 1 to 5 m), clay-based buffer material (2.5 m), soil vegetation layer (0.3 m) are placed above the mound after the trench is filled and the mound is shaped by VLLW packages covered with sand [4].

SL-LLW and SL-ILW disposal

First SL-LLW and SL-ILW disposal facilities in the UK, France and Hungary were similar in their designs to those currently used for VLLW disposal purposes: simple trenches and mounds filled with RW packages and a multi-layer screen installed above. However, certain difficulties associated with ensuring robust isolation of radionuclides with no additional safety barriers constructed were revealed during the operation of such near-surface DF for short-lived RW [5, 6].

To date, evolution of RW disposal approaches has resulted in the use of quite complex engineered structures in SL-LLW and SL-ILW disposal designs (France, Spain, Belgium) involving concrete enclosing structures fitted with systems enabling to drain potential leakages, as well as control and monitoring systems.

France with its CSA site was among the first countries to implement the modern SL-LLW and SL-ILW surface disposal concept: CSA designs were developed based on the experience gained from the construction and operation of CSM operated from 1969 to 1994. CSA structure is a reinforced 25 m wide and 8 m high concrete module composed of a number of compartments. RW packages are installed into these compartments using bridge or overhead travelling crane operated under temporary mobile roofs. As the compartments are filled with RW packages, the void space in-between is

Figure 3. Surface DF RW for SL-LLW and SL-ILW in France [1]

backfilled with sand and bentonite mixture. Concrete is poured from the above at the compartments filled up with waste shaping a reinforced concrete cube. A mound-shape multi-layer cover is installed after the disposal modules are filled and all compartments are encased in concrete [7].

CSA disposal facility has been operated in incident-free mode since 1992. The engineering solutions applied in its designs are successfully used by other countries: similar engineering designs have been applied in the development of RWDFs in Spain [8], Lithuania [9], Ukraine [10].

In Belgium, similar surface disposal concept but with additional engineering solutions in place enabling to monitor the RW packages state has been implemented for SL-LLW and SL-ILW disposal purposes. Belgian DFRW (figure 4) is fitted with a gallery designed to inspect and check the state of the disposal facility [11, 12].

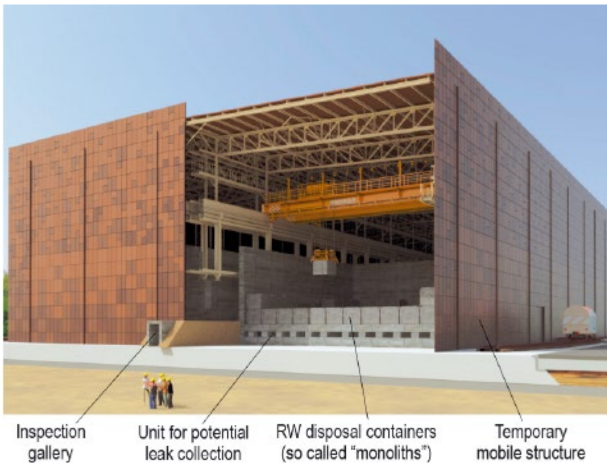

Figure 4. Design of a surface DFRW for SL-LLW and SL-ILW in Belgium [4]

Thus, at the initial stages of the DFRW operation the disposal facility can be considered as a long-term storage facility for RW allowing for package retrieval.

In a number of countries SL-LLW and SL-ILW waste shall be disposed of in underground DFRWs located at a depth of up to 100 m (Sweden, Finland — crystalline rocks) and even deep DFRW at a depth of over 400 m (Germany — salt formations, Switzerland — clay formations).

Olkiluoto repository in Finland (figure 5) features two vertical silos (for SL-LLW and SL-ILW) excavated in crystalline bedrock at a depth of 60—100 m. The silos are bridged with a common assembly hall connected with the surface facilities via an inclined ramp used for radioactive waste transportation by purpose-designed vehicles. Another underground repository for SL-LLW and SL-ILW disposal located in crystallin bedrock is being operated at the site of Loviisa NPP [14].

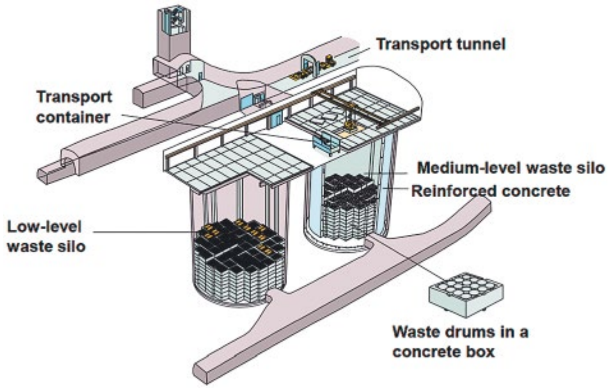

Figure 5. VLJ Olkiluoto repository design [16]

SFR underground repository in Sweden designed for SL-LLW and SL-ILW disposal (figure 6) was constructed at a depth of 60 m in the crystalline bedrocks in the vicinity of Forsmark NPP. It involves a 70 m deep (including a disposal part of 53 m) silo being 28 m in diameter. The silo is intended for the disposal of concrete containers containing SL-ILW. There are also four 160 m long tunnels designed for concrete and metal SL-LLW container disposal. In 2014, SKB applied for SFR extension. The envisaged extension provides for the construction of six 240—275 m long horizontal tunnels at a depth of 120—140 m (beneath the existing disposal level) connected to the surface DFRW facilities via an inclined 1.7 km long ramp. In case of a positive decision on the extention, total SFR capacity including the additional sections will amount to some 200,000 m^3 of RW [15].

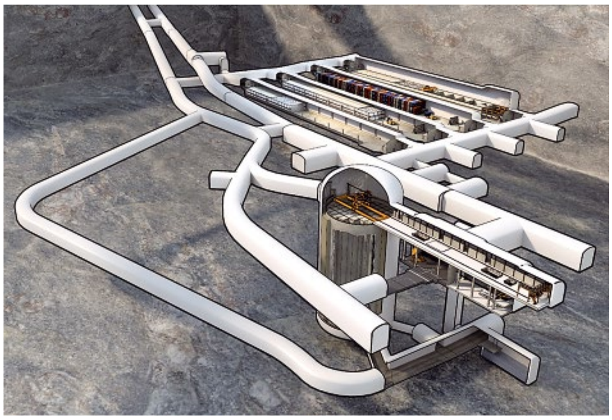

Figure 6. SFR design layout — underground disposal facility in the vicinity of Forsmark NPP [17]

Deep DF RW for SL-LLW and SL-ILW has been operated in Hungary since 2012. The capacity of this repository located in Bataapati region amounts to 40,000 m^3 of waste generated from Paks NPP operation. Its excavations are located in crystalline rocks at a depth of some 250 m. Bataapati repository accepts concrete containers containing drums with solid or immobilized RW. Void space between the drums is grouted. The use of steel containers for SL-LLW is considered as a potential disposal option enabling to increase the disposal capacity [18].

Conceptual designs of a SL-LLW and SL-ILW repository were developed in Switzerland. The designs suggest RW disposal at a depth of some 400 m in clay formations. The repository structure involves an array of 200 m long horizontal tunnels excavated in parallel and connected at their end with a transport tunnel. Underground structures are connected with the surface facilities via two vertical shafts (ventilation and technological) and an inclined ramp designed for the RW container transportation to the disposal level [19].

Disposal of LL-LLW and LL-ILW

French conceptual project provides for two disposal options for LL-LLW containing radium, C-14 and other long-lived radionuclides suggesting their emplacement in clay formations:

- using trenches at a depth of 15—30 m;
- using a network of horizontal excavations at a depth of 50—200 m.

Capacity of the planned DF RW will account for some 180,000 m^3. Siting stage is going to be finalized by 2019 followed by the detailed development of engineering and design solutions [20]. In France, LL-ILW are planned to be disposed of together with HLW in Cigeo disposal facility [21].

In Belgium, LL-LLW, LL-ILW, HLW and SNF (in case if it's decided to stop its reprocessing) are planned to be disposed of in a deep DFRW constructed in clay formations at a depth of 220 m using two disposal tunnels each being 3 m in diameter and 1,000 m long. Particular site for the repository construction hasn't been chosen yet. Boom clay and Ypresian clay are considered as potential bedrocks for repository construction [22].

In Sweden, LL-LLW and LL-ILW are planned to be disposed of in SFL — a deep DFRW. Currently, the conceptual designs are being developed, the siting efforts, as well as relevant R&Ds are being carried out. According to SKB plans, the project itself will launched not earlier than 2035 [23].

In Hungary, a deep DFRW is planned to be constructed in crystalline bedrocks to allow LL-LLW, LL-ILW, HLW and SNF disposal. R&D program should be completed by 2030. Underground research laboratory is planned to be constructed and relevant field R&Ds implemented by 2054. DFRW construction and relevant licensing process will take place in 2055—2063 with the operation itself started in 2064 [1].

Disposal of HLW and SNF

In keeping with IAEA recommendations and relevant provisions of national legal frameworks, HLW and SNF shall be disposed of in deep DFRWs (SNF in countries with open nuclear fuel cycle).

In Sweden, development of SNF and HLW repository has been implemented since 1970's in keeping with the so called KBS-3 concept. The selected DWRW site is located in the vicinity of Forsmark NPP. The repository is planned for construction in a granitoid mass at a depth of some 500 m (figure 7).

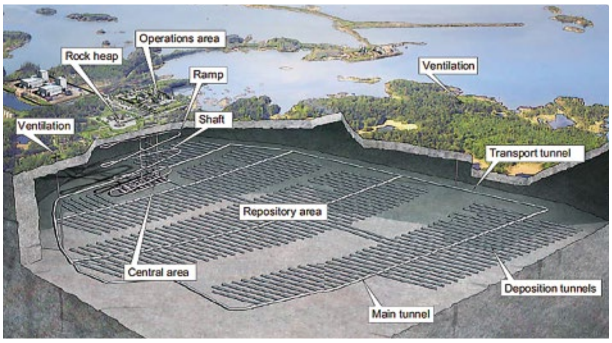

Figure 7. Design of the DFRW according to the KBS-3 concept [24]

Underground facilities involve a central section with a spiral ramp, connecting it to the surface facilities and enabling SNF transportation, four vertical shafts for non-process load delivery, ventilation and excavated rock retrieval, as well as a network of tunnels with boreholes for SNF container emplacement drilled in their foundation [25].

Containers for spent fuel assemblies (SFAs) being 4.8 m high with a diameter of 1.05 m and wall thickness of 50 mm are manufactured of refined copper. A metal insert is installed inside of each SFA container. Gross container weight is 24.6 tons.

In Finland, SNF repository site (ONKALO) is located in the vicinity of Olkiluoto NPP. Practical efforts at the site have been started in 2004 and according to the existing plans should be finalized by 2020.

ONKALO engineering solutions were developed based on the Swedish KBS-3 designs. ONKALO disposal concept suggests waste emplacement at a depth of 420 m. Copper containers with SFAs are emplaced vertically into 7.8 m deep boreholes (each borehole should contain only one container) with a diameter of 1.75 m. Boreholes are located at a distance of 9 m between each other and connected with a horizontal tunnel (disposal tunnel) on the top. DFRW includes dozens of disposal tunnels shaping a network of a total area of 1.5 km^2. 5 km long transportation tunnel and three shafts (inlet/exhaust ventilation shafts and personnel shaft) provide access from the surface to the underground structures.

In France, disposal of HLW and LL-ILW is planned to be started in 2025 under the CIGEO project. CIGEO facility is located at the boundary of two regions — Meuse and Haute de Marne in the north-eastern part at the depth of some 500 m in argillite bedrocks (figure 8).

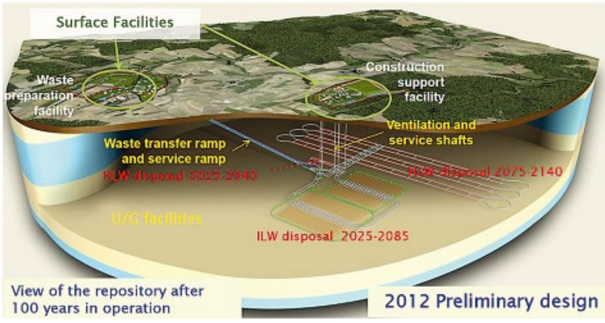

Figure 8. CIGEO repository design concept [26]

Design solutions have been developed allowing to dispose of 73,500 m³ of LL-ILW (180,000 containers) and 10,000 m³ of HLW (60,000 containers).

Underground facilities are composed of horizontal excavations interconnected by tunnels involving into two areas: one for LL-ILW disposal and the other — for HLW disposal.

Waste transportation from the surface is carried out using a funicular moving along a 5 km long inclined track. Relevant vertical shafts are constructed to enable ventilation at the disposal level, delivery of materials, as well as retrieval of excavated rocks.

Intermediate-level waste are planned to be disposed of in stainless steel cannisters placed in pairs into reinforced concrete containers. Containers are to be stacked into levels inside horizontal excavations of a rectangular shape.

Primary packages with high-level waste (stainless steel canisters) will be emplaced into thick walled cylindric steel containers. These containers will be placed one after the other inside 100 m long horizontal tunnels lined with steel. These tunnels are oriented radially outwards the main transportation tunnel used for HLW delivery. HLW and LL-ILW disposal technology was developed accounting for the possibility of further retrieval of already disposed waste packages.

In Switzerland, construction of HLW and SNF repository should start in 2050's. It's planned to emplace such waste into clay formations at a depth of some 600—800 m. Along with HLW, the repository will accept LL-ILW. According to design concept, HLW and SNF are to be disposed of inside 800 m long horizontal tunnels with a diameter of 3 m excavated parallelly and connected at their end with the transportation tunnel. The distance between the tunnels should be about 40 m. The void space between the walls of the disposal tunnel and the packages with HLW or SNF is planned to be backfilled with granulated bentonite. HLW or SNF packages should be placed at a distance of 3 m from each other. A 8 m thick barrier layer made of benthonite blocks and pallets should be installed between each 10 consecutively placed packages. Long-lived ILW are planned to be disposed of in 200 m long parallel tunnels [27].

In Germany, despite significant achievement in the development of HLW repository project (salt formations of Gorleben), active siting efforts seeking for disposal in alternative bedrocks are being implemented. This is mainly due to the fact that salt formations are not commonly considered for RW disposal in Europe. Large clay formations in the north of the country and relatively moderate clay mass in the south are currently being considered as prospective ones for repository siting [28].

Conclusion

During the past decades, European countries have accumulated vast knowledge on the development and operation of near-surface disposal facilities for VLLW, SL-LLW and SL-ILW. Comprehensive R&Ds are being implemented to study the issues associated with LL-LLW, LL-ILW, HLW and SNF deep disposal.

Table 2 summarized engineering solutions depending on the types of repositories designed for different RW categories, adopted or being developed in a number of European countries.

Sallow and surface structures are used for VLLW disposal purposes. Their safety is ensured by protective underlying and overlying screens.

Near-surface repositories both of surface and underground type located at a depth of up to 100 m are used for SL-LLW and SL-ILW disposal purposes.

Italicized are the repositories being at the design stage of development

Since first surface DFRW were created, RW disposal technologies have changed significantly. Structure elements of modern surface DFRWs provide for concrete enclosing structures, drainage of seepage water and the opportunity to retrieve already disposed waste packages (if deemed necessary), thus, literally converting such structures into storage facilities for the whole time period associated with active controls.

Underground DFRWs for SL-LLW and SL-ILW disposal are operated in Sweden and Finaland,

Table 2. Data on repository types operated and developed in a number of European countries

<table>
<tr><th rowspan="2">Repository type</th><th colspan="4">RW category</th></tr>
<tr><th>VLLW</th><th>SL-LLW, SL-ILW</th><th>LL-LLW, LL-ILW</th><th>HLW, SNF</th></tr>
<tr><td>Surface</td><td>Sweden, France, Spain</td><td>UK France Spain Hungary Belgium</td><td></td><td></td></tr>
<tr><td>Underground (up to 100 m)</td><td></td><td>Sweden (1) Finland (1)</td><td>France (2)</td><td></td></tr>
<tr><td rowspan="7">Depth</td><td></td><td></td><td colspan="2">France (2)</td></tr>
<tr><td></td><td></td><td colspan="2">Belgium (2)</td></tr>
<tr><td></td><td></td><td>Sweden (1)</td><td>Sweden (1)</td></tr>
<tr><td></td><td></td><td></td><td>Finland (1)</td></tr>
<tr><td></td><td>Germany (3)</td><td>Germany (2)</td><td>Germany (4)</td></tr>
<tr><td></td><td>Switzerland (2)</td><td colspan="2">Switzerland (2)</td></tr>
<tr><td></td><td>Hungary (1)</td><td colspan="2">Hungary (1)</td></tr>
</table>

Notes: 1 — crystalline rocks, 2 — clay rocks, 3 — salt formations, 4 — iron mills.

Germany and Hungary. In Switzerland, short-lived waste is planned to be disposed of in a deep repository.

As it comes to LL-LLW, LL-ILW, HLW and SNF disposal, relevant practical experience is not yet available. However, most of European countries have already developed deep repository designs for such RW. In general, same deep DFRWs are supposed to accept both LL-LLW/LL-ILW and HLW/ SNF.

Bedrocks considered as potential formations for underground and deep DFRW construction include crystalline rocks (Sweden, Finland, Hungary), clays (France, Belgium, Germany, Switzerland) and salts (Germany).

Brief analysis of engineering solutions applied in Europe both at already available RW disposal facilities and those being at the design stage of development has revealed the diversity of approaches in the disposal technologies considered and enabled to identify general trends in achieving higher safety level of RW disposal facilities:

- shallow disposal structures are no longer used for SL-LLW and SL-ILW disposal purposes giving preference to either surface or underground structures excavated at a depth of some tens – hundreds of meters;
- almost complete rejection of salt formations and clear tendency suggesting the use of clay rocks in the countries where these formations are available;
- use of technologies allowing for the retrieval of already disposed waste packages at the stages associated with active controls.

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Bibliographic description

Sorokin V. T., Pavlov D. I. Technologies of Radioactive Waste Disposal: European Experience and Trends. *Radioactive Waste*, 2018, no. 4(5), pp. 24—32. (In Russian).