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THE COST OF RADWASTE DISPOSAL: FOREIGN ASSESSMENTS

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The paper discusses cost estimation approaches and the main factors influencing the cost of radioactive waste (RW) disposal. It presents the data on the cost for a number of already available and developed disposal facilities for radioactive waste (DF RW) and spent fuel (SNF). The paper summarizes the estimates on the costs of different types of disposal facilities (surface, underground, deep).

Key words: *radioactive waste, disposal facilities, life cycle of disposal facilities, the cost of disposal facilities, fees for radioactive waste disposal.*

Introduction

Most of the countries with developed nuclear power sector are currently implementing globally accepted concept of RW management suggesting waste conditioning and disposal.

All countries that ratified the Joint Convention on the Safety of Radioactive Waste Management and the Safety of Spent Nuclear Fuel Management to withdraw the burden from future generations, all the countries that have undertaken certain obligations according to which they have to establish special reserve funds to cover RW disposal liabilities [1]. For this reason, issues associated with the establishment of special reserve funds, the costs and waste disposal tariffs are crucial for all the countries making relevant decisions on the final stage of RW management.

State-of-art of RW disposal projects in European countries and the proposed technologies has been overviewed in a number of publications [2—6].

Objectives of the present paper can be summarized as follows:

- Identifying international approaches on RW disposal cost assessment;
- Evaluation of factors impacting RW disposal costs;
- International evaluations and comparison of costs associated with development and operation of DFRW, as well RW disposal tariffs;
- Identifying the ways for reducing RW disposal costs.

DFRW lifecycle

The complex nature of the objectives specified for the present paper is mostly due to specific national aspects being individual for each country in terms of cost assessment approaches, differences in the designs, design development and DFRW construction timeline, as well as the need of taking into account relevant cost estimates for the entire lifecycle of considered DFRW.

DFRW's lifecycle involves 4 stages (table 1). Each stage is characterized by a specific set of operations considered typical for it.

Table 1. Lifecycle stages for a DFRW and the list of key activities

Pre-operational	Operational	Closure	Moni-toring
R&Ds Siting Licensing R&Ds including safety case development Construction of the start-up section and infrastructure facilities	Licensing Disposal of waste packages in DFRW compartments Construction of subsequent DFRW's sections Monitoring	Licensing Construction of safety barriers	Active controls Passive controls

Pre-operational stage involves all the activities required to construct and to commission a DFRW. For all disposal facilities currently available abroad, this stage is characterized with lengthy siting process and decision making on the optimal site location, large-scale R&Ds aiming to demonstrate the safety of engineering solutions proposed. In a number of countries operating NPPs and implementing projects on the development of disposal facilities for HLW and long-lived ILW, this stage has been lasting since 1970's—1980's.

At the operational stage, disposal facility is filled up with RW disposal packages. Duration of this stage mostly depends on DFRW capacity. However, in a number of countries (for example, Belgium), a concept suggesting long-term monitoring over DFRW state before its closure has been established, thus, significantly extending the duration of the operational stage and practically suggesting that at this stage the facility can be considered as a long-term storage facility.

DFRW closure stage provides for the construction of safety barriers ensuring radionuclide containment within the disposal system and preventing possible external impacts on RW packages. Relevant construction technologies applied at DFRW closure stages, provide for concrete casting, backfilling the voids with buffer material, construction of multilayer covering screens and other methods.

DFRW closure stage is followed by site and environmental monitoring involving two stages: active and passive controls. At active monitoring stage, samples taken from observation wells and boreholes are analyzed, the state of safety barriers is assessed, regular maintenance of "caps" (for near surface DF RW) is provided with security assurance and other activities being implemented as well. Passive controls stage involves institutional controls at the disposal site and, in certain cases, some security measures being implemented. It should be noted, that monitoring process irrespective of its nature is implemented at all DFRW lifecycle stages [7].

For different types of RW disposal facilities, duration of design development, construction and operational stages varies from several decades to over 100 years. On average, DFRW lifecycle (from the initial stage till the end of active controls stage) accounts for:

- 100 years for VLLW;
- 300—500 years for LLW and short-lived ILW.

For long-lived ILW and HLW/SNF, duration of the active controls stage is still being discussed [7].

Figure 1 shows the breakdown of costs and their ratios at different stages of HLW disposal facility's lifecycle [8].

Construction is seen as a most costly stage in the life cycle of DFRW since the disposal structure operation requires the establishment of an extensive infrastructure. Construction stage is marked with maximum costs.

Depending on DF RW capacity, operational costs can cumulatively exceed the construction ones, but nevertheless are significantly stretched in time. For example, construction costs (2033—2042) for Canadian disposal facility with a capacity of 3.6 mln SFAs (compact SFAs being 50 cm in length discharged from CANDU type reactor units) amount to $ 3.8 billion (in 2016 prices), and operating costs (2043—2072) — to $ 9.4 billion [9].

For countries spreading across a big territory, the bigger part of the costs at operational stage is associated with RW transportation. According to estimates, total transportation cost for the Yucca Mountain project in the US [10] for the entire operational period (2017—2073) would account for some $ 20.2 billion (in 2007 prices) accounting for one fifth from the total cost of the disposal project implemented at this site.

The length of the initial stages (R&Ds, design development, siting, licensing) varies significantly country by country. The reason behind is the complex nature of forecasts associated with R&D findings, social, political and economic factors, possible regulatory changes during this period. For example, in France and Germany development of LLW/ILW disposal projects has been ongoing since 1980's. However, French DFRW CSA (with a capacity of 1,000,000 m^3 of RW) has been operated since 1992, whereas commissioning of the German DFRW Konrad (with a design capacity of 650,000 m^3) is scheduled only for 2021.

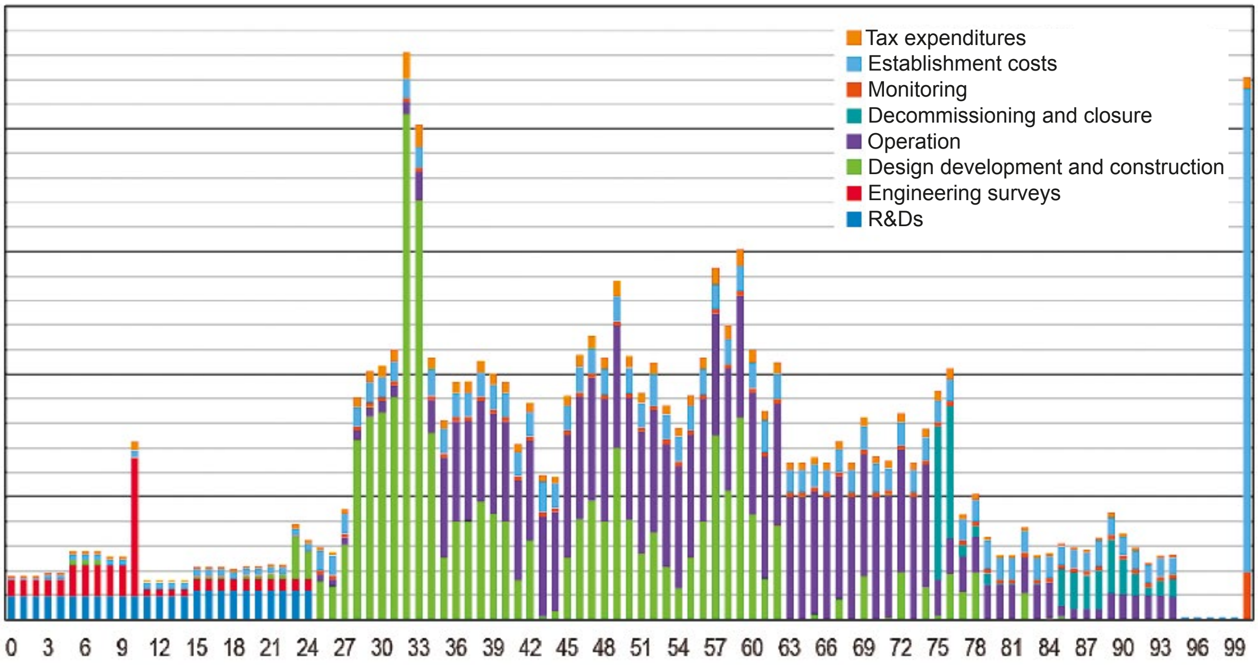

Figure 1. Breakdown of DFRW lifecycle costs (10 years — siting efforts involving the selection of potentially suitable sites for DFRW construction, 15 years — decision making on the selection of a particular site for DFRW construction and development of RW disposal technology, 10 years — DFRW construction, 40 years — operation, 20 years — decommissioning of buildings and structures, DFRW closure, 300 years — institutional control (cost of this stage is given in a summarized way in column "100 years")

Given the length of DFRW lifecycle and uneven distribution of costs by time, costing mechanisms addressing RW final disposal challenge are characterized by some specific features.

Principles and mechanisms of RW disposal funding

Polluter pays principle is widely used as the main principle considered during the establishment of financial mechanisms in the field of RW management. This principle is reflected in environmental regulations of many countries ensuring the decrease in the amounts of RW generated thanks to the introduction of improved processing and conditioning technologies and enhanced operating culture.

RW disposal costs are covered from funds established based on the charges collected from each MWh of electricity produced. A quite common global world practice suggests the establishment of specialized organizations managing these funds, as well as national companies responsible for RW disposal itself: Andra in France, DBE Technology in Germany (since 2018 renamed as GBE Technology), SKB in Sweden, Ondraf/Niras in Belgium and etc.

The amount of annual deductions to the funds may vary depending on the priorities specified at the national level for RW management programs, profit indicators, inflation rates and other factors. In Sweden, for example, a tendency demonstrating the decrease in the amount of deductions to RW management fund has manifested itself [8, p. 52].

Given the fact that the funds are established prior to DFRW construction and should cover all the needs addressing the challenge of RW final isolation, responsible organizations provide for various financial instruments ensuring long-term funding of the disposal projects, for example, by investing the funds into some other projects. Forecasts on the use of funds are being developed for various levels of inflation and nuclear industry development scenarios (extension of NPP operating time, early shutdown of NPPs and other scenarios).

Although, in general, these financial approaches addressing final disposal issues are developed and enable to address long-term and costly projects, the challenge of decreasing RW disposal costs still seems to be quite pressing. In this respect, evaluation of key factors impacting the disposal costs is believed to be quite helpful.

Factors affecting RW disposal costs

National legal, regulatory and technical framework in the field of RW management (RW classification system, technical specification, sanitary rules) is considered as most significant factors affecting disposal costs. Such key factors can be nominally divided into two categories: (a) technical and (b) social and political. Considering the importance of public acceptance, social and political factors play an important role in RW final disposal matter. These questions being discussed in [12, 13] are believed to be beyond the scope of the present paper.

Technical factors affecting RW disposal costs are as follows:

- The capacity of disposal facility;
- Waste characteristics (activity, composition, heat output);
- RW disposal container types;
- Type of construction: near-surface (surface, underground) or deep disposal;
- Disposal facility's site (available infrastructure, remoteness from waste suppliers, geological features);
- Retrievability of waste;
- Length of site and environmental monitoring.

According to the study performed [14—16], key factor affecting the specific cost of RW disposal accounts for disposal facility's capacity (volume). Evaluation of the dependency between the cost covering the disposal of 1 m^3 of RW and the design capacity of disposal facility [16] demonstrates manifold (figure 2) reduction in the specific RW disposal cost upon the increase of its design capacity. This explains global trend towards the construction of large centralized waste disposal facilities. Courtiers generating big amount of waste (the United Kingdom, France) are operating disposal facilities with a design capacity of some 1,000,000 m^3 of waste.

Given the dependences presented in figure 2, development of multinational disposal facilities seems to be quite a feasible option for countries generating relatively small amounts of RW. These issues have been discussed by IAEA and other organizations [17—19], in particular as a possible option for East European countries. However, to date, due to some inconsistencies associated with sociopolitical and legal factors the issue was not brought to a close. Activities associated with the development of multinational repository in Europe are currently run by ERDO (European Repository Development Organization).

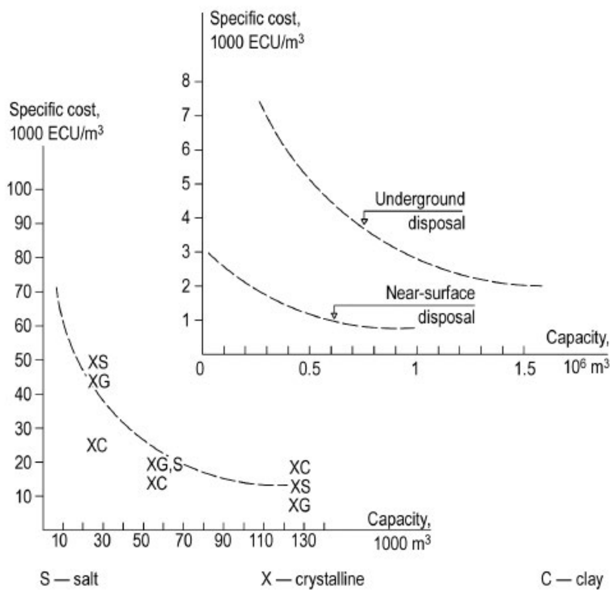

Figure 2. RW disposal cost vs. RW disposal facility's capacity (bottom left — for long-lived ILW and HLW, top right — for LLW and short-lived ILW) [16]

Heat output is yet another RW characteristic along with RW activity and long-lived radionuclide content, being considered as a key factor affecting RW disposal costs (for HLW/SNF). Owning to the fact that in RW disposal facilities, the distance between HLW packages is defined based on the requirement on non-exceeding the temperature of the surrounding bedrock, long-term HLW/SNF storage may ensure some significant decrease in the heat emitted by waste packages, thus, providing for denser emplacement of waste inside the repository. For example, under French disposal project CIGEO an increase in HLW storage time by 20 years enabled to reduce the space area of the underground repository section by approximately 35 % [20] (figure 3).

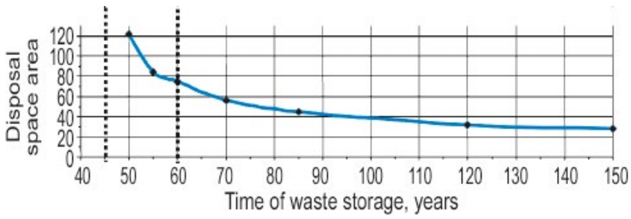

Figure 3. HWL disposal space area vs. HLW cooling time in a long-term storage facility (French HLW disposal project CIGEO, clay formations) [20]

Under the development of SNF final disposal concept KBS-3 followed by Sweden and Finland, a study was performed to evaluate the dependency between the costs associated with KBS-3 implementation and orientation of disposal boreholes (vertical/horizontal). According to [21], horizonal orientation of boreholes enables to save some 300,000,000 € for the Swedish repository project (also given the fact that horizontal orientation allows to install bigger number of SNF containers into a single borehole).

Study on the cost of LLW and short-lived ILW disposal [14] discussed different types of repository structures (surface/underground). The research has shown that:

- The cost of surface repositories is lower than of underground ones (for example, in Hungary, where both design options with approximately equal capacity (30—40 thousand m^3) have been implemented, the difference accounted for about 30 %);

- Operational costs for surface and underground disposal facilities are quite similar.

At the same time, the study specifically noted that, despite the higher cost of underground disposal facilities' construction, it would be premature to conclude that the final cost of RW underground disposal facilities exceeds the cost of surface disposal. Underground disposal may provide savings due to the following reasons:

- reduced monitoring time;
- more rational use of surface areas;
- no need to cover the costs for construction and maintenance of a covering screen provided for surface repositories;
- infrastructure solutions (for example, in Sweden, SFR repository siting under the bottom of the Baltic Sea in close proximity to the Forsmark NPP allowed optimal use of the existing NPP infrastructure for RW disposal purposes).

Repository depth also affects the cost of its construction. According to [15], with every 250 m of going down, repository[1] cost increases by about 10 %.

No detailed study has been done to date to investigate the impact of bedrock type (crystalline/clay/salt) on waste disposal costs. However, in the US, a comparative cost analysis has been performed for different SNF/HLW disposal concepts and different types of potential bedrocks (crystalline/clay/salt) given repository's design capacity of 140,000 tons. According to [22], the cost of SNF disposal for 2012, reduced to 1 kg of spent fuel would amount to:

- 571 $/kg for clay disposal concept;
- 579 $/kg for SNF disposal in crystalline rocks;
- 232 $/kg for SNF disposal in salts.

Furthermore, the cost of drilling and rock excavation for all three options studied turned to be quite similar.

Type of disposal containers significantly impacts final RW disposal cost. The cost of most expensive containers for HLW/SNF disposal currently amounts to some 100—250 thousand $ per package [22], which depending on particular project, is considered either as capital or operational costs. However, decrease in container cost does not necessarily result in a proportional decrease in RW disposal costs. Table 2 summarizes the data on specific cost of ILW disposal in the United Kingdom depending on the waste container applied.

Dramatic increase in the specific cost of disposal option suggesting the use of unshielded container is due to the fact that in this case significantly increased are the costs associated with waste transportation, additional measures ensuring staff protection and construction of additional safety barriers inside the repository.

Table 2. Specific cost of ILW disposal in the UK based on container type applied (according to [23])

Container type	Container cost	Disposal cost
Metal (stainless) unshielded container 3 m^3	45,000£	10,000 £/м^3
Reinforced concrete shielded container 6 m^3	3,900 £/м^3	30,000 £
Cast iron shielded container DCIC 9 m^3	120,000 £	3,900 тыс. £/м^3

The cost of LLW containers to a lesser extent affects the one of disposal, as these containers generally do not fulfill the barrier function in the repository system and do not provide biological protection. In the United Kingdom, ISO based containers are used for LLW disposal purposes the cost of which is normally less than 2—3 thousand £ per piece.

Study of retrievable disposal options [24] has demonstrated that the possibility for RW package retrieval seems feasible to be provided for no more than 100 years. According to [25], HLW/SNF disposal project implemented in the Netherlands requires around € 1.8 million to be spent annually on maintaining the surface part of the repository "open" providing relevant opportunities for waste package retrieval.

Cost indicators for foreign waste repositories

Variety of engineering solutions proposed under different national RW disposal projects implemented in different countries, as well as the diversity of national legal frameworks, historical, sociopolitical and other factors result in substantially different disposal costs (table 3).

In countries with a more developed market component of the economy (United States, United Kingdom), DFRW operators set tariffs for the disposal of their own in consultation with state regulatory authorities. In a number of countries, tariffs are established entirely by state organizations having appropriate responsibilities. However, in both cases, tariffs are determined taking into account DFRW cost indicators and specific aspects of national legislation.

For example, LLW disposal tariffs in Great Britain for 2016 were established at a level of 3,038 £/m^3, in the US these accounted for 3,300—33,300 $/m^3 [26] depending on the waste class (A, B, C) in accordance with the classification adopted in the US.

For long-lived ILW and HLW/SNF disposal facilities a tendency can be observed suggesting an

[1] According to data on deep repositories for HLW/SNF

Table 3. Cost indicators for some RW disposal projects implemented abroad

Country	Repository characteristic	Economic indicators			Notes
		Capital investment	Operational costs	Total costs	
Near-surface disposal facilities (surface or located at a depth of less than 100 m)					
Sweden SFR 1988 – till present	Waste: SL-LLW, SL-ILW Depth – 60 m Capacity – 63, 000 m^3	0.74 bln SEK (in the prices of the late 1980's)	0.03 bln SEK /year (in the prices of the late 1980's)	1.5 bln SEK (in the prices of the late 1980's)	[27] Capacity is panned to be increased up to 140,000 m^3
Sweden Oskarshamn 1986–2025	Waste: VLLW Surface DFRW Capacity – 10,000 m^3	No data available	100–200 $/$m^3$ (in the prices of the late 1980's)	No data available	[27]
Belgium Dessel 2016	Waste: SL-LLW, SL-ILW Surface DFRW Capacity – 69 ,900 m^3	No data available	No data available	0.8 bln € (in 2010 prices)	[3, p. 20]
France Aube 1992 – till present	Waste: SL-LLW, SL-ILW Surface DFRW Capacity – 1 mln m^3	No data available	0.035 bln $ (in the prices of the late 1990's)	0.25 bln $ (in the prices of the late 1990's)	Disposal cost accounts approximately for 8,000 FRF/m^3 (in the prices of the late 1990's) [3, p. 132]
Canada NSDF ChalkRiver 2020	Waste: SL-LLW, SL-ILW Surface DFRW Capacity – 1 mln m^3	0.173 bln $ (in 2017 prices)	No data available	0.6 bln $ (in 2017 prices)	[28]
Deep DFWR					
Finland Onkalo 2022–2120	Waste: 5,500 t SNF (2,800 containers) Depth 400 m	0.802 bln $ (in 2009 prices according to [8])	0.918 bln $ (in 2009 prices according to [8])	1.72 bln $ (in 2009 prices according to [8]) 3.9 bln € (in 2017 prices according to [31])	[8, p. 163] [31]
Sweden KBS 2030's	Waste: 12 ,000 t SNF Depth 470 m	2.553 bln $ (in 2009 prices)	1.665 bln $ (in 2009 prices)	4.22 bln $ (in 2009 prices.)	[8, p. 163]
Germany Konrad 2022	Waste: non-heat generating LLW, ILW Depth 800–1,200 m Capacity 300,000 m^3	0.9 bln € (borehole reconstruction) 0.93 bln € (geological survey) (in 2009 prices according to [3])	0.0185 bln €/year (in 2009 prices according to [3])	3.4 bln € (in 2016 prices according to [29])	[3, p. 54] [29]
Belgium Boom clay 2035 – LL-ILW, LL-LLW 2080 – HLW	Waste: 11,100 m^3 LL-LLW, LL-ILW, 600 m^3 HLW Depth – 220 m	HLW: 1.481 bln $ ILW/LLW: 2.082 bln $ (in 2009 prices)	HLW: 0.335 bln $ ILW/LLW: 0.529 bln $ (in 2009 prices)	HLW: 1.82 bln $ ILW/ LLW: 2.61 bln $ (in 2009 prices)	[8, p. 163]
Czech Republic	Waste: SNF Depth – 500 m Capacity up to 10,000 t SNF	0.917 bln $ (in 2009 prices)	1.546 bln $ (in 2009 prices)	2.46 bln € (in 2009 prices)	[8, p. 163]
Spain	Waste: SNF Depth – no data available Capacity up to 7,000 t SNF	1.192 bln $ (in 2009 prices)	0.993 bln $ (in 2009 prices)	2.18 bln € (in 2009 prices)	[8, p. 163]
France Cigeo 2025	Waste: HLW, LL-ILW Depth – 500 m Capacity – 70–80 thousand m^3	19.8 bln € (in 2012 prices)	8.8 bln € (in 2012 prices)	34.4 bln € (in 2012 prices)	[30]
Canada	Waste: SNF Depth – 500 m Capacity – 108,000 t SNF	3.801 bln $ (in 2015 prices)	9.441 bln $ (in 2015 prices)	18.33 bln $ (in 2015 prices)	[9, p. 4]

increase in the cost of relevant projects during their implementation. For example, in 2005, the cost of French Cigeo repository was estimated to be 16.5 billion €, and in 2014 the cost increased to 34.4 billion € [30]. According to [8], the cost of Finnish DFRW Onkalo (2013) was estimated as equal to 1.72 billion €. Currently, the cost of Onkalo is estimated as 3.9 billion € [31].

Ways of reducing RW disposal costs

Key area in the development of engineering solutions for RW final disposal accounts for identifying an optimal rate between repository cost and its safety indicators. Figure 4 presents the curves showing the dependency between DFRW costs, safety criteria and key engineering factors.

Development of national strategies addressing final RW disposal challenges is often preceded by feasibility studies aiming to find an optimal ratio between repository cost and safety indicators. For LLW and ILW disposal purposes, these studies are currently being performed in a number of East European countries (Belarus, Lithuania, Slovenia [32]).

The following areas are considered as the basic ones providing a decrease in RW disposal costs:

- Decrease in the amount of waste generation and conditioning;
- Selection of an optimal duration of heat-generating HLW storage;
- Increasing the repository capacity;
- Selection of optimal infrastructure repository siting solutions;
- Use of reference disposal technologies (enabling to reduce the costs associated with R&Ds and design development).

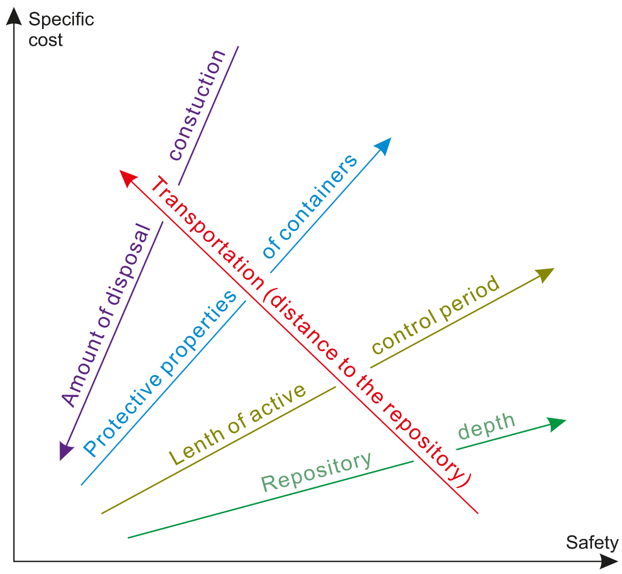

Figure 4. Key factors affecting the specific cost and RW disposal safety (basic dependency)

Conclusion

Evaluation of RW disposal costs at the stage of decision-making on repository development, is essential for the development of special funds and identifying waste disposal tariffs, as well as the choice of design solutions.

RW disposal costs depend on radiation and thermophysical characteristics of the waste, type, design and capacity of the disposal facility, duration and amount of research, development, design and exploration activities, legal framework, social, economic and national aspects being specific for each country.

The cost indicators presented for operating and developed RW repositories refer to different types of repository structures, their capacity and operational conditions. Thus, qualified comparison and identification of stable dependencies between various factors seems to be impossible.

The lack of such dependences, availability and diversity of factors affecting RW disposal cost indicates the possibility and necessity of performing preliminary comprehensive feasibility studies aimed at enhancing the efficiency of decision-making on site selection and repository structure type, conditions with relevant timeframes for repository operation, closure and monitoring.

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