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Improved conceptual design of LILW repository

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Abstract

Given the forthcoming need for the construction of a repository for low and intermediate radioactive level waste in the Republic of Croatia, this paper proposes a repository design which is, from a geotechnical point of view, simple, practical and safe, and significantly improved considering current conceptual designs. Existing low and intermediate radioactive level waste repositories are mostly vault-type, near-surface constructions with some kind of covering (top) system of protective layers. However, most of these repositories do not have a bottom protective system, apart from concrete flooring (base). The reasons for such designs include the presumed longevity of the waste packages (containers), which are mostly reinforced concrete and/or steel containers. Considering that the concrete is a material which will, under certain conditions, deteriorate (e.g. dissolution of the cement matrix), and so potentially release radionuclides to the environment, it is essential to design the repository in such a manner that all forms of early release of radionuclides are prevented. The improved conceptual design of low and intermediate radioactive level waste repository presented in this paper is intended to provide an improved containment of radionuclides from waste and ensure the long term safety of the repository. This paper is the first in a series which will cover the basic design of the repository, systems of protective layers and preliminary slope stability analyses.

Keywords:

Repository; LILW; Design; Protective Layers

1. Introduction

The main goal of low and intermediate level radioactive waste (LILW) repositories is to ensure the long-term isolation of radionuclides by preventing their migration into the environment until their activity falls to a negligible level. In order to ensure long-term isolation, it is necessary to take into account the location of the repository (geological environment of the selected site) and the repository design, with a technical solution based on a system of multiple engineered barriers.

The International Atomic Energy Agency's (IAEA) near-surface disposal options (generic disposal concept categories) are defined as (**IAEA 1992; IAEA, 2001a**):

- a covered trench,
- a closed vault,
- a domed vault,
- an open vault.

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Typically, there are three basic types (see **Figure 1**) of near-surface and shallow LILW repositories (**Crossland, 2012**):

- above ground (i.e. surface),
- below ground (i.e. sub-surface vaults),
- silo (i.e. sub-surface silo).

Usually the choice among these types/concepts of disposal is based upon the level of the groundwater, and the avoidance of water contact with the waste. It is considered that, in dry climatic conditions, there is no need for additional barriers apart from the waste packages (**Crossland, 2012**) and older, landfill type, repositories, were mostly built with no additional barriers either below or above the waste. Many such repositories have since reported the early release of radionuclides since the waste packages (steel drums, mostly) corroded leading to the release of radionuclides - the dry climate was proven to be not dry enough. One of the first repositories which was improved and provided with the additional covering (top) system of protective layers (TSPL) was

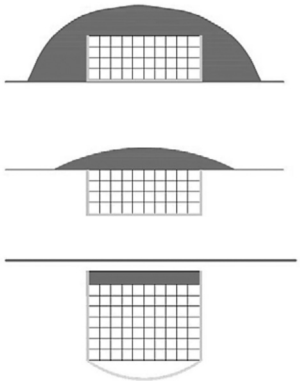

Figure 1: Three typical types of near-surface repositories: above ground, below ground and silo (acc. to **Crossland, 2012**)

Drigg in the UK (**Ashworth et al., 1997; Clegg et al., 1997; Coyle et al., 1997**). Several other repositories have undergone some kind of remediation and installation of additional protective layers (see **Table 1**). However, few repositories have a bottom system of protective layers (BSPL), especially not a complex one.

Table 1: Remediated repositories

REPOSITORY	REFERENCE
Hanford, WA USA	**Keller & Stewart, 1991** **Gephart, 2003**
Barnwell, SC, USA	**Han et al., 1997** **DHEC, 2000** **NCRPC, 2007**
Beatty, NV, USA	**US ECOLOGY, 1992** **Striegl et al., 1996** **NDPBH, 2016**
Maxey Flats, KY, USA	**BHS, 1976** **Zehner, 1979**
West Valley, NY, USA	**Grant et al., 1987** **Parrott, 1999**
Richland, WA, USA	**ATSDR, 2011**
Maišiagala, Lithuania	**Mazeika et al., 2001** **Gudelis et al., 2006** **Ragaišis et al., 2021**
Centre de la Manche, France	**Lidskog & Andersson, 2002** **Bergström et al., 2011** **Dutzer et al., 2012**

It is possible to divide LILW repositories into several groups, depending not just on their position (above/below ground) and the presence or absence of groundwater, but based on primary waste containment system and top and bottom protective layers, hence, a detailed review of disposal concepts is given in **Table 2**.

With respect to the protective layers, there are usually four types of barriers that can be used in some kind of grouping to isolate the waste after closure of the repository: advection-resistant barrier (liner), conductive barrier (drainage layer for meteoric water), infiltration control, and vegetated soil cover (recultivation layer). Systems of multiple engineering barriers (SMEB) in both the TSPL and BSPL, designed in a way to ensure long term containment of LILW is usually not considered. Generally, disposal facility design relies on waste packaging and solidification of waste or massive amounts of concrete to ensure long term performance of the repository. If only the TSPL is applied it must resist erosion, freeze-thaw cycles, and biological intrusion, and therefore is designed to be of sufficient thickness and made of suitable materials to protect the repository from external influence. Usually, the impermeability performance of the TSPL cannot be guaranteed over several hundred years without maintenance or repairs, so even if the construction materials are selected for their long-term durability, the TSPL should also be designed to minimize maintenance and repair.

It can be concluded that, for a LILW disposal facility, since it must perform for hundreds or thousands of years, the design has to be adapted to site specific geological, topographical and climatic conditions. However, several other parameters must also be considered, i.e. the amount and type of waste, costs of disposal, societal and political issues. Although the latter two are not engineering problems, they will impact the safety case and the design of the repository since it is necessary to prove quality and functionality of the disposal facility to all stakeholders, and that may require adjusting the design.

2. Examples of concepts for near-surface LILW disposal facilities

Selection of the concept for a Croatian LILW disposal facility began in 1984-1988 with the Croatian-Slovenian agreement and the beginning of the search for a common solution for the disposal of spent nuclear fuel (SNF) and LILW (**Schaller, 1997**). At that time, exploration for a suitable location in Croatia for a shallow repository (tunnel type, **Figure 2**) and, in Slovenia, a suitable location for a near surface disposal facility with engineered barriers (see **Figure 3**) was initiated. Later, after the breakup of Yugoslavia, the LILW disposal programmes parted ways and have undergone several changes, one of which was abandonment of the tunnel type repository concept in Croatia in favour of a near surface disposal facility with engineered barriers. However, the current Croatian programme is based upon long-term storage of LILW and the site selection for the disposal facility has not yet been initiated (**Croatia, 2018**).

Considering the Croatian geological environment, climate, and other factors for the disposal facility site selection (**Perković et al., 2020**), the probable concept for the disposal facility in Croatia will be either a "Surface concrete vault", a "Near-surface closed concrete vault" or a "Deeper concrete vault" (see **Table 2**). The selection of these concepts lies in the existing plans for the construction of the future LILW repository in Croatia (**Schaller,**

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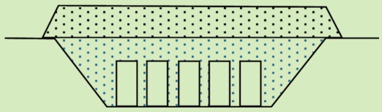
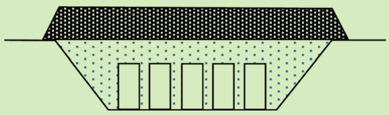
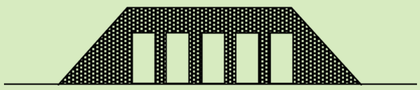
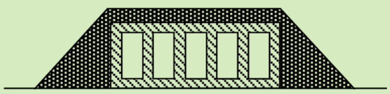
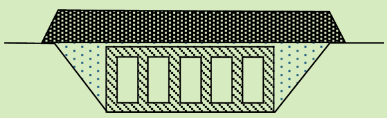
Table 2: Disposal concepts for LILW repositories (modified from **Garamszeghy, 2021**)

CONCEPT	EXAMPLE	SCHEMATICS	COMMENTS
Trench – unlined	Drigg, UK (**Ashworth et al., 1997;** **Clegg et al., 1997;** **Coyle et al., 1997)** Hanford, WA, USA (**Keller & Stewart, 1991; Gephart, 2003)** Vaalputs, SAR (**IAEA, 2001b**) Ezeiza, Argentina (**Jinchuk, 2001**)		• Below ground, near surface • Waste covered with local material (soil gathered during the excavation of trenches) • Easy construction, inexpensive • Under certain circumstances, waste packages can deteriorate quickly • Significant subsidence • Susceptible to biological intrusion • Suitable for very low-level radioactive waste (VLLW) and low level waste (LLW)
Trench - lined	El Cabril, Spain (**IAEA, 2001b**)		• Below ground, near surface • Waste covered with selected protective layers • Easy construction, inexpensive • Waste packages can deteriorate quickly • Significant subsidence • Susceptible to biological intrusion • Suitable for VLLW and LLW
Mound	Forsmark Sweden (**SWEDEN, 2017**) Oskarshamn Sweden (**SWEDEN, 2017**) Ringhals Sweden (**SWEDEN, 2017**) Studsvik Sweden (**SWEDEN, 2017**) Manche disposal facility (*Centre de Stockage de la Manche* – CSM), France (**IAEA, 2001b, Dutzer et al., 2012; Bergström et al., 2011; Lidskog & Andersson. 2002**) Fernald OH, USA (**RAC, 1998**)		• Above ground • Waste covered with selected protective layers • Easy construction, inexpensive • Suitable for large volumes of waste • Waste packages may deteriorate quickly • Susceptible to biological intrusion • Waste above ground water-table • Significant subsidence • Suitable for VLLW and LLW
Surface concrete vault	Aube disposal facility (*Le Centre de stockage de l'Aube* – CSA), France (**Fernique, 1993**) El Cabril, Spain (**IAEA, 2001b**) Drigg, UK (**Ashworth et al., 1997; Clegg et al., 1997; Coyle et al., 1997**) Beilong, China (**Fan et al., 2013**); Mochovce, Slovakia (**Garamszeghy, 2021**)		• Above ground • Modular, vault type • Waste covered with selected protective layers • Susceptible to biological intrusion • Waste above ground water-table • Suitable for LLW
Near-surface closed concrete vault	Aube disposal facility, France (**Dutzer & Nicolas, 1997**) El Cabril, Spain (**Zuloaga, 1997**) Rokkasho-mura, Japan (**Sakabe, 1997**) Trombay, India (**IAEA, 2001b**); Tarapur, India (**Balu et al., 1977a**); Maišigala, Lithuania (**Mazeika et al., 2001;** **Gudelis et al., 2006;** **Ragaišs et al., 2021**)		• Below ground • Modular, vault type • Waste covered with selected protective layers • Waste in packages or treated • Vault closed with concrete lid, sealed (filled) with concrete • Susceptible to biological intrusion • Waste above ground water-table • Suitable for LLW and limited amounts/volumes of intermediate level waste (ILW)

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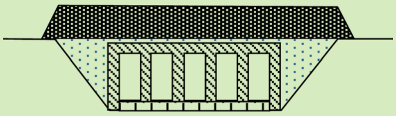
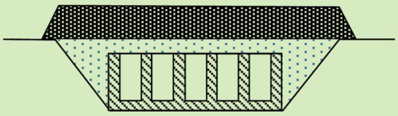
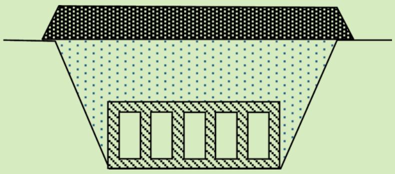
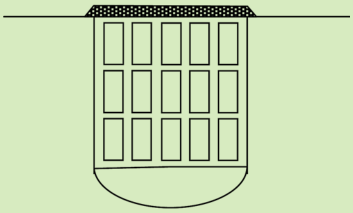
CONCEPT	EXAMPLE	SCHEMATICS	COMMENTS
Near-surface domed concrete vault	IRUS, Canada (**Charlesworth & Champ, 1997**)		• Below ground • Modular, vault type • Infiltration is controlled by placing waste in a dry permeable layer (a hydraulic cage) and covered with an impermeable concrete roof • Waste covered with selected protective layers • Waste in packages or treated • Susceptible to biological intrusion • Waste above ground water-table • Suitable for LLW and limited amounts of ILW
Near-surface open concrete vault	Drigg, UK (**Ashworth et al., 1997**)		• Below ground • Modular, vault type • A low permeability cap (selected protective layers) is placed over the filled vault without emplacement of a concrete slab • Waste is pre-treated (minimized voidage) • Some subsidence (accommodated by covering protective layers) • Susceptible to biological intrusion • Waste above ground water-table • Suitable for LLW and limited amounts of ILW
Deeper concrete vault	Rokkasho-mura, Japan (**Sakabe, 1997**) Dounreay, Scotland (**DOURNEAY, 2022; IAEA, 2001b**)		• Below ground • Modular, vault type • Waste covered with selected protective layers • Waste in packages or treated, different sizes and masses of packages • Vault closed with concrete lid, sealed (filled) with concrete • More resistant to biological intrusion than surface or shallow vaults • Waste above ground water-table • Suitable for LLW and limited amounts of ILW
Underground silo	Vrbina, Slovenia (**IAEA, 2020c**)		• Below ground • Silo type • Waste covered with selected protective layers • Waste in packages (concrete containers) • Silo sealed (filled) with concrete • More resistant to biological intrusion than surface or shallow vaults • Waste above or at the ground water-table • Suitable for LLW and limited amounts of ILW

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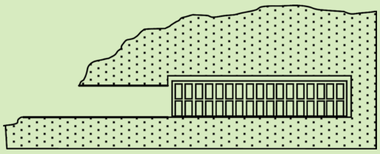
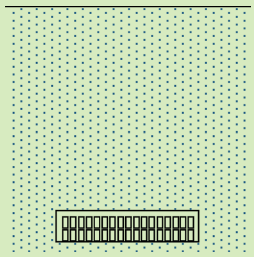
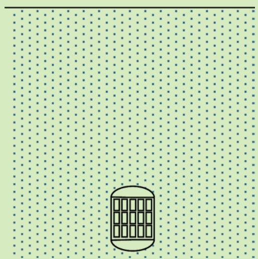
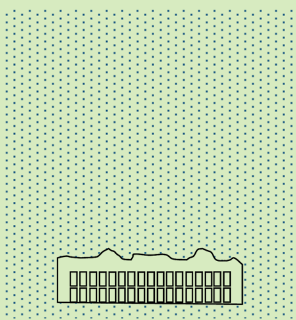
CONCEPT	EXAMPLE	SCHEMATICS	COMMENTS
Shallow underground space	Himdalen, Norway (**Saanio et al., 2021; Sörlie, 2001**)		• Below ground • Tunnel type • Waste in packages (concrete vaults) sealed (filled) with concrete • More resistant to biological intrusion than surface or shallow vaults • Can be constructed in wide range of geological media • Waste above or under the ground water-table • Suitable for LLW and ILW
Deeper underground space – purpose-built tunnel/cavern	Loviisa, Finland (**Aikas and Anttila, 2008; Nummi, 2019; STUK, 2017**) Forsmark, Sweden (**SWEDEN, 2017; Carlsson at al., 1997**) Olikluoto, Finland (**Aikas and Anttila, 2008; STUK, 2017**)		• Below ground • Cavern type • Requires large initial investment for surface infrastructure (i.e. access ramps, hoists, shafts, ventilation, etc.) • Access capacity significantly limits waste mass and package size • Waste in packages or large vaults sealed (filled) with concrete • Intrusion resistant • Can be constructed in wide range of geological media • Waste under the ground water-table • Suitable for LLW and ILW
Deeper underground space – purpose-built silo	Olikluoto, Finland (**Aikas and Anttila, 2008; FINLAND. 2022; STUK, 2017**) Forsmark, Sweden (**Sweden, 2017; Carlsson et al., 1997**) Wolsong, Korea (**Beyon et al., 2020**)		• Below ground • Silo type • Requires large initial investment for surface infrastructure (i.e. access ramps, hoists, shafts, ventilation, etc.) • Access capacity significantly limits waste mass and package size • Waste in packages sealed (filled) with concrete • Intrusion resistant • Waste under the ground water-table • Suitable for LLW and ILW
Deeper underground space – converted mine	Morsleben, Germany (**Brenecke & Martens, 1997; Lempert & Biurrun, 1999**) Asse, Germany (**GERMANY, 2017; Bracke et al., 2002**) Richard II, Czech Republic (**Garamszeghy, 2021; Duda, 2008; CZECH REPUBLIC 2008; Woller, 2008**) Baita Bihor, Romania (**Garamszeghy, 2021; IAEA 2020b; Dragolici et al., 2005**)		• Below ground • Converted mine • Access capacity significantly limits waste mass and package size • Waste in packages sealed (filled) with concrete or some concrete based mixture • Intrusion resistant • Problems with complexity of underground spaces and geological environment • Waste under the ground water-table • Suitable for LLW and ILW

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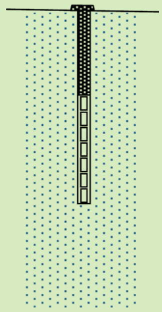
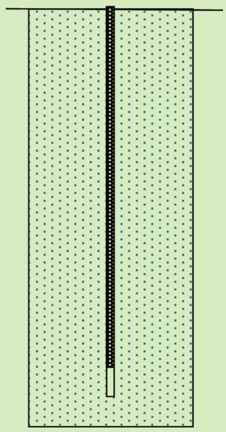
CONCEPT	EXAMPLE	SCHEMATICS	COMMENTS
Shallow borehole	Novi Han, Bulgaria (**Kolev et al., 2000; Stefanova and Mateeva, 2001**) Püspökszilágy, Hungary (**Garamszeghy, 2021; Ormai et al., 2001; Ormai, 2003**) Rajasthan, India (**Garamszeghy, 2021; Balu et al., 1977b**) Mt Walton East, Australia (**EPA, 2000; Hartley et al., 1998**) Moscow SIA "Radon", Russia (**Sobolev et al., 2001; Tkachenko et al., 2012; Sobolev et al., 2002; Dmitriev et al., 2007**) USDOE Facility, NV, USA (**USDOE, 1996; USDOE, 2011 USDOE, 2016; USDOE, 2017; USNWTRB, 2016**)		• Below ground • Shallow borehole • Depth and diameter will depend upon waste packages (from 20 cm up to couple of meters if 200 l barrels are emplaced three at level around central axis) • Waste package size limited by borehole diameter • Sealed (filled) with concrete • More resistant to biological intrusion than surface or shallow vaults • Could be constructed in wide range of geological media • Waste under the ground water-table • Usually used for the disused sealed sources (DSS) or smaller amounts of ILW
Deep borehole	Seversk, Russia (**IAEA, 2020; ROSATOM, 2017**) Zheleznogorsk, Russia (**IAEA, 2020a; ROSATOM, 2017**) Oak Ridge, TN, USA (**Stow & Haase, 1986; Rustick, et al., 2015**)		• Below ground- deep borehole • Waste package size is limited by small borehole diameter • Usually used for DSS or smaller amounts of liquid ILW • Can be designed for high level waste (HLW) • Sealed (filled) with concrete • More intrusion resistant than shallow boreholes • Waste under the ground water-table

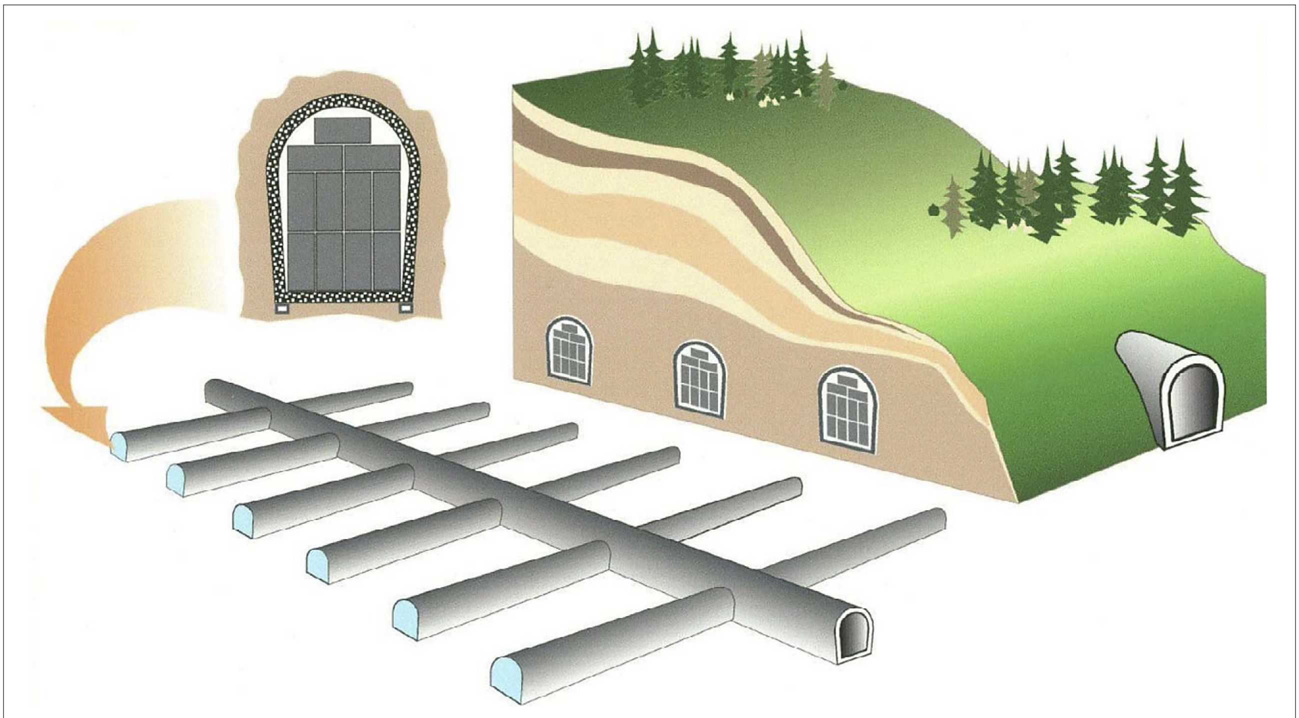


Figure 2: Tunnel type shallow repository for LILW (**APO, 2000**)

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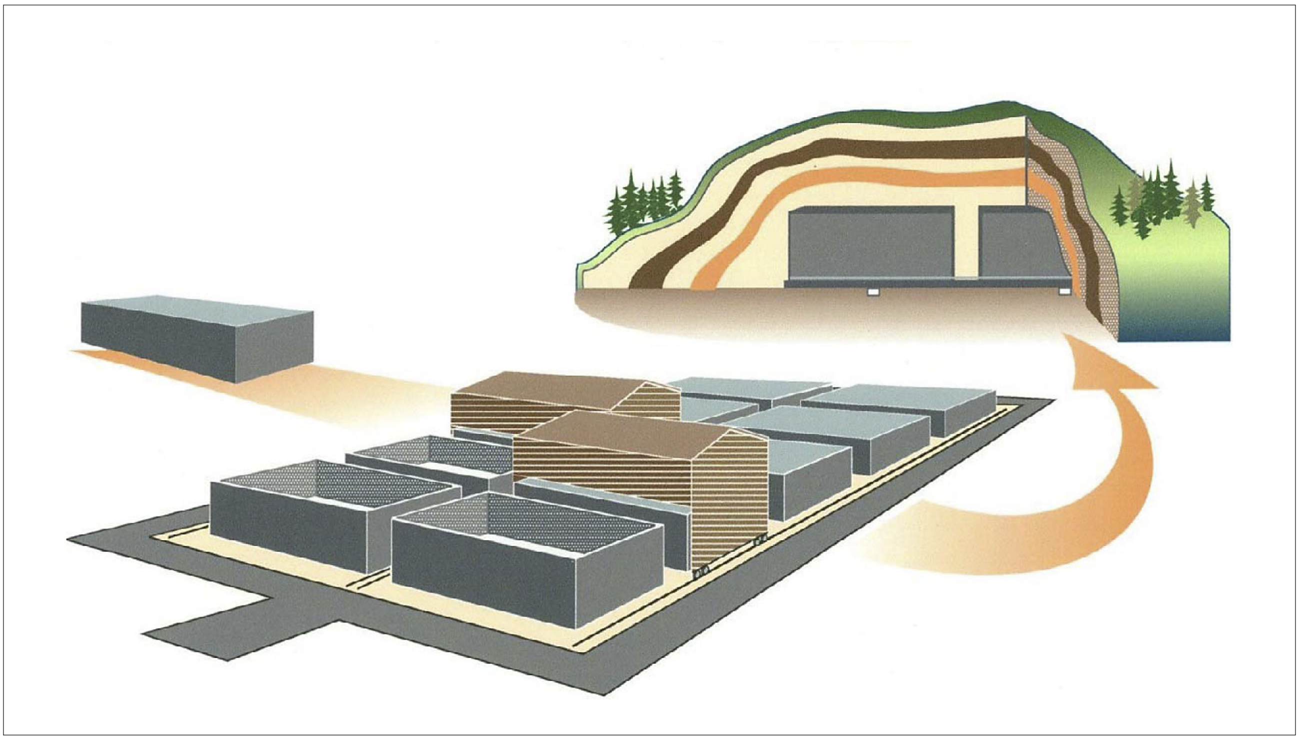

Figure 3: Near surface disposal facility with engineering barriers for LILW (**APO, 2000**)

1997), and that some concepts are outdated and cannot be considered safe enough (Trench – unlined; Trench - lined; Mound; Near-surface domed concrete vault ; Near-surface open concrete vault), potentially intended for small amounts of material (Shallow borehole; Deep borehole), there are no suitable facilities in Croatia (Deeper underground space – converted mine) or the conceptual solution assumes high investments, may include potential problems with the complex geological environment or complex geotechnical works (Deeper concrete vault; Underground silo; Shallow underground space; Deeper underground space – purpose-built tunnel/cavern; Deeper underground space – purpose-built silo).

In order to begin the selection of the probable concept, without having an actual disposal site, but understanding the Croatian geological environment and other specific site selection factors (cf. **Perković et al., 2020**), it is necessary to consider existing state-of-the-art disposal facilities elsewhere where the best practice is being applied. Five examples of such facilities whose design would be appropriate for the disposal facility in Croatia are described below.

2.1. Aube disposal facility

Aube disposal facility (Le Centre de stockage de l'Aube – CSA), France (**Fernique, 1993; Dutzer & Nicolas, 1997; Poitier, 1999; Bergström et al., 2011**) began operation in 1992. It accepts short-lived LILW from the French nuclear power plants (NPP) and the activities of the French atomic energy commission (CEA) along with LILW from medicine, research and industry (MRI).

The Aube repository is constructed on sediments – a sand aquifer ('draining formation' in **Figure 4**) underlain by a clay aquiclude ('impermeable substratum' in **Figure 4**) "where sand drains all precipitation waters towards a single outlet, the Noues d'Amance River downstream from the disposal facility" (**Poitier, 1999**). Although such geological conditions would not be acceptable in Croatia (**Croatia, 2018**), considering the possibility of ground water and river contamination, for CSA the clay aquiclude under a sand aquifer "constitutes a natural barrier against release of radioactive elements into the groundwater, and thus prevents any dispersion into the environment" (**Fernique, 1993**).

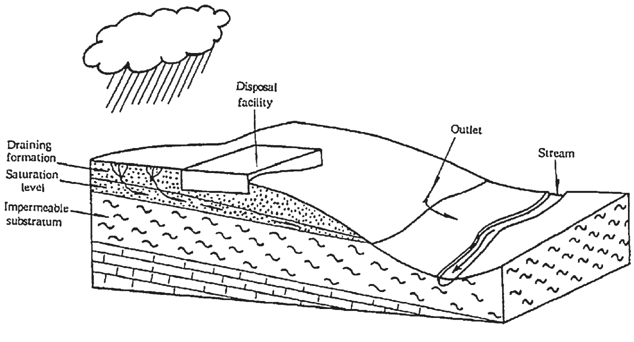

Figure 4: Geology of the Aube disposal facility (**Fernique, 1993**)

The safety of such a disposal facility relies on (**Bergström et al., 2011**):

- The quality of waste packages.
- The repository structures (vaults) in which the packages are placed.

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- The geology of the location which represents a long-term natural barrier.

CSA is an above ground facility ("Surface concrete vault", **Table 2**) with engineered barriers (see **Figure 5**). The waste packages are placed into reinforced concrete vaults (25 m2 of usable area, 8 m high) with 0.3 m thick walls. About 400 vaults will be, depending on waste type, backfilled with "either gravel or concrete, and then topped with a concrete slab and sealed with an impermeable coating" (**Bergström et al., 2011**). When the facility will be closed, vaults will be covered with "a several metres thick layer of clay, to ensure the long-term confinement of the waste" (**Bergström et al., 2011**). The disposal facility is, as many others of this type, equipped with inspection concrete pipes under the repository, for drainage and radionuclide release control.

Figure 5: Aube disposal facility disposal concept (**ANDRA, 2011**) (1) waste package, (2) the final cap, (3) the geological environment of the site (clay aquiclude overlain by a sand aquifer)

The thickness of the concrete vaults is calculated to provide mechanical strength and containment of radionuclides for a period of a few hundred years. For the safety assessment of a near surface repository, Andra "*refers to a basic safety guide which advises that, at the end of the monitoring period (up to 300 years), safety should no longer depend on the artificial barriers but on the properties of the site*" (**Bergström et al., 2011**).

The main disadvantage of Aube disposal facility's design is the thick natural sand aquifer which is supposed to drain infiltrating meteoric water but can also be a radionuclide leakage pathway. BSPL is, therefore, natural.

2.2. El Cabril

El Cabril (*Almacén Centralizado de Residuos Radiactivos de Baja y Media Actividad El Cabril*) is a surface concrete vault repository for short-lived LILW, located at a former uranium mine in Cordoba, Spain (**IAEA, 2001b**). The facility receives all LILW generated in Spain and is operated by Enresa, the organisation responsible for the management of radioactive waste in Spain. The repository began operation in 1992. Attached to El Cabril is a treatment plant for LLW and a disposal facility for VLLW. The institutional control of the El Cabril repository is expected to be 300 years, much the same as for the Aube disposal facility.

The El Cabril repository relies on three barriers to reduce the release of radionuclides into the environment (**Bergström et al., 2011**):

- The conditioned waste and the containers.
- The engineered structures (vaults) housing the waste.
- A barrier (liner), formed by the natural terrain of the location at which the facility is located (i.e. natural attenuation).

The engineered structures – concrete vaults above ground, have walls and a base of ca. 0.5 m thick, and the base is covered with a polyurethane waterproof layer and a 10–20 cm thick layer of porous concrete. Beneath the vaults is a drainage control system with inspection galleries (see **Figure 6**).

After filling the vaults, a multi-layer engineered TSPL will be built to redirect meteoric water and provide long-term protection of the vault. TSPL will consist of "*a series of earth and clay layers*" (**Bergström et al., 2011**) (see **Figure 7**) to isolate the vaults from the biosphere and ensure their integration into the landscape. The TSPL include (**Zuloaga, 1997**) a layer of topsoil (recultivation layer), soil (freeze-thaw barrier), coarse gravel, a first sand layer, a liner (clay), a second sand layer, a "*damp proof course and a third draining sand layer*" (**Bergström et al., 2011**).

El Cabril, along with Aube does not have a BSPL, apart from concrete flooring which includes an inspection gallery, and relies solely on waste packages and the TSPL for the protection against meteoric water infiltration and biological intrusion.

2.3. Drigg

The Drigg (UK) Low Level Waste Disposal Site has been in operation since 1959 and, being one of the first radioactive waste disposal sites in the world, the original disposal concept included the open disposal of waste, in different packages and states of matter, into trenches excavated, more or less, at random. The cover material was excavated soil (at first), which later changed to a low permeability cover to limit meteoric water infiltration. In the 1980s, the site was significantly improved, and the vault concept was adopted (**BNFL, 2002**). The modern trenches at the Drigg LLW disposal site are approximately 5 m below the surface (to the base of vaults) and, to control and prevent horizontal groundwater flow, a cement-clay cut-off wall was constructed and connected to a low permeability layer under the repository.

The newest part of the facility is a near-surface open concrete vault (see **Table 1**) with a low permeability cover (see **Figure 8**). As with the rest of the facility, these

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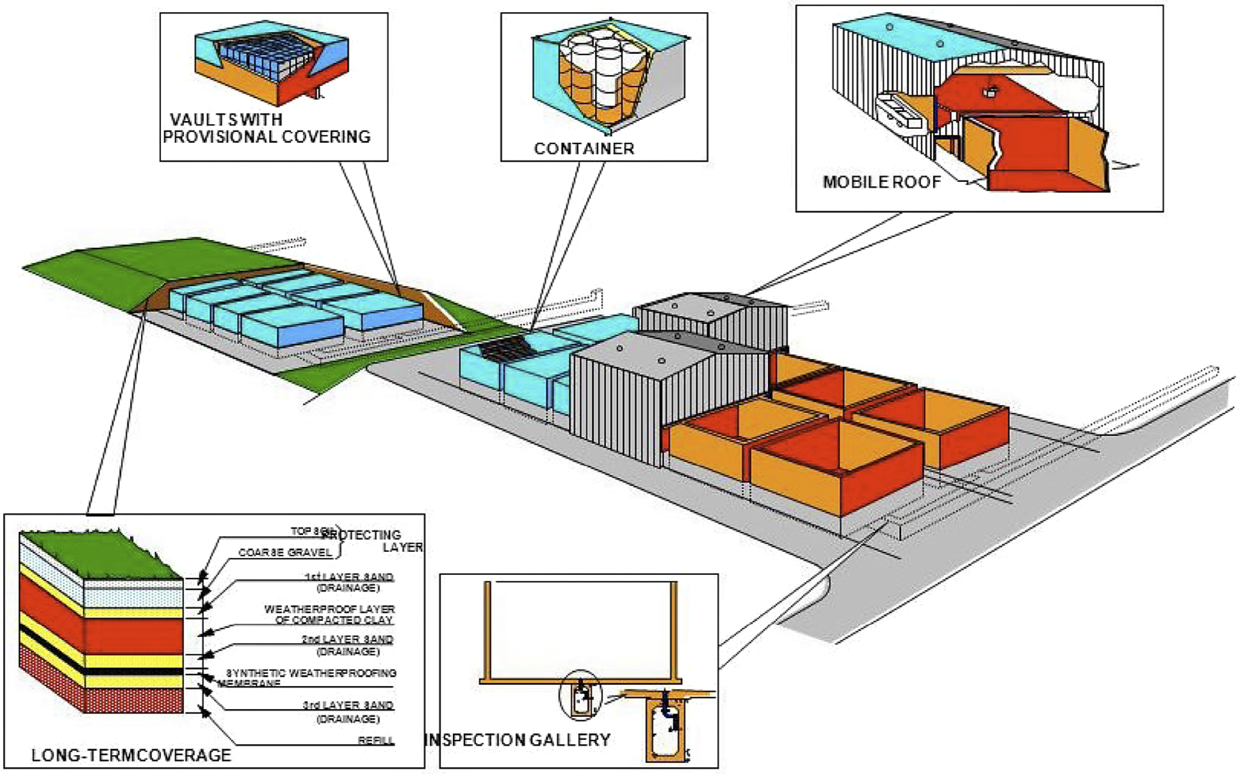

Figure 6: El Cabril disposal facility disposal concept (**Zuloaga, 1997**)

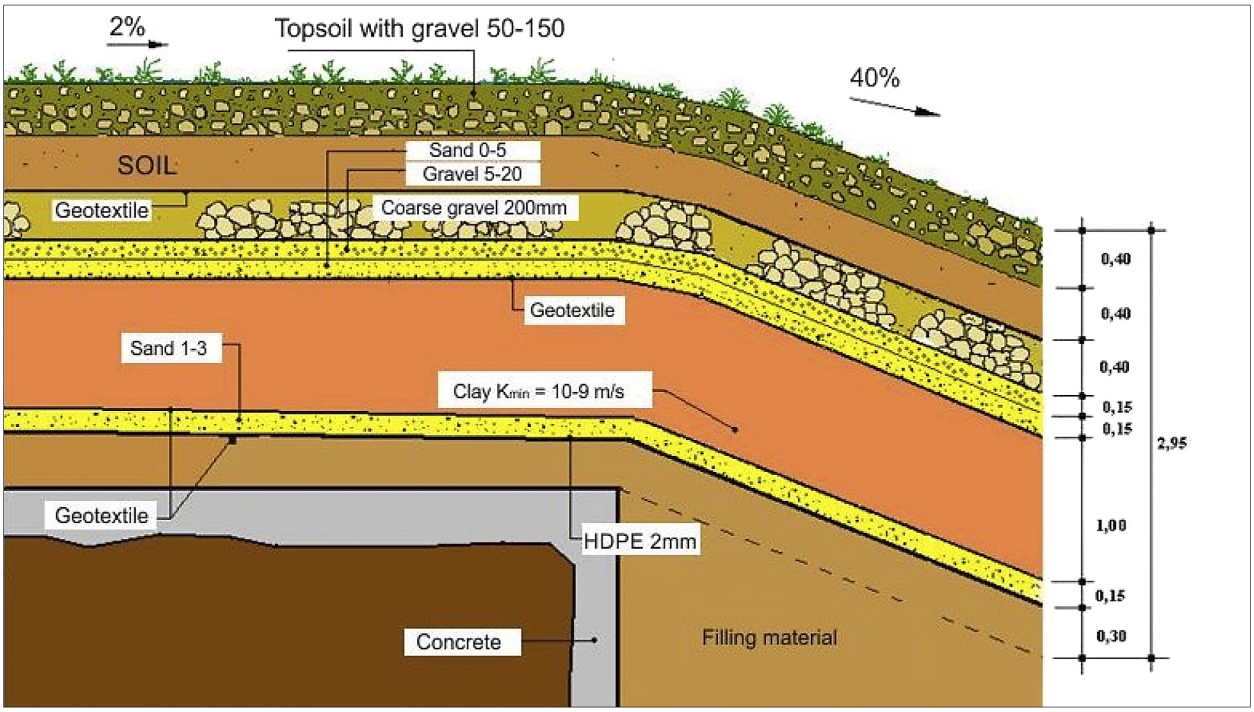

Figure 7: Top system of protective layers at El Cabril LILW disposal facility (**Zuloaga, 1997**)

vaults rely on the local geological environment, predominantly on the sub level low permeability layer and the aforementioned cement-clay cut-off wall, for long-term performance. Obviously, it was easier to perform remediation of the site than to relocate all the material disposed on the site since 1959. However, it would be more prudent to think about additional protective systems, e.g. a low permeability curtain, where bentonite clay would be used.

At closure, the space between and around the waste packages will be backfilled with cement grout for struc-

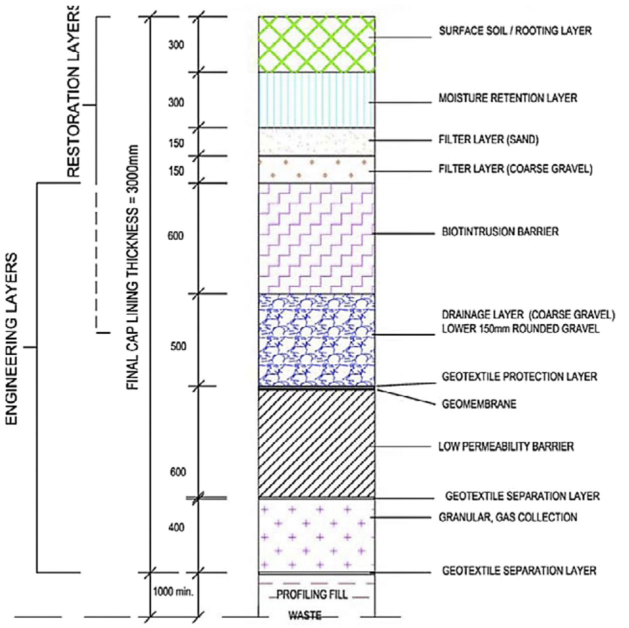

Figure 8: Top system of protective layers at the Drigg LLW disposal facility (LLWR, 2015)

tural stability and radionuclide containment purposes. After sealing with concrete, the vaults will be capped with a TSPL. After closure, a 100-year monitoring and institutional control is planned.

2.4. Rokkasho

An example of a deeper sub-surface vault (see **Table 1**) is the Rokkasho-mura, Japanese repository for short-lived LILW. It has been operational since 1992 and includes two disposal facilities, both of which include a number of concrete vaults constructed in a deep trench excavated in the local bedrock. The first vault is approximately 24x24x6 m, constructed at a depth of about 15 m below the surface. The vault is divided into cells 6x6x6 m, each large enough to receive up to 320 X 200 L drums. The second vault is 36x37x7 m, constructed at a depth of about 20 m below surface and contains 36 cells of 6x6x6 m, holding up to 360 X 200 L drums (**Garamszeghy, 2021**).

The construction of cells and the cross-section of the disposal trench with vaults is shown in **Figure 9**.

In **Figure 9** it is clearly shown that the Rokkasho-mura repository relies on the local geological environment as BSPL and, as a TSPL against meteoric water infiltration and biological intrusion, a combination of waste packages, concrete vaults, protective/filling material (bentonite/sand mixture) and a thick cover soil layer are used.

3. The new proposed concept

Since there have been no recent developments in the generic concept for the future Croatian LILW disposal facility, nor has a location been chosen, it is assumed that some form of vault repository will be designed. The reasons for that are as follows:

- Trench concepts (both unlined and lined) are either obsolete or predominantly intended for a dry climate with a minimum of precipitation.
- The mound concept does not provide a sufficient degree of performance, especially if the disposal of ILW is considered.
- Near-surface domed concrete vaults and near-surface open concrete vaults are constructions whose vaults are not completely sealed, and are therefore likely to have reduced long-term performance.
- An underground silo is a technically complicated object whose structural integrity can be endangered due to stress redistribution in the facility through cycles of excavation, concreting and waste filling. Also, some wastes (e.g. bitumen) and seals (e.g. bentonite) will swell and can fracture the silo.
- A shallow underground space – tunnel type of disposal facility, requires a specific topographical and geological environment.
- Deeper underground space concepts (purpose-built tunnel/cavern and/or purpose-built silo), although

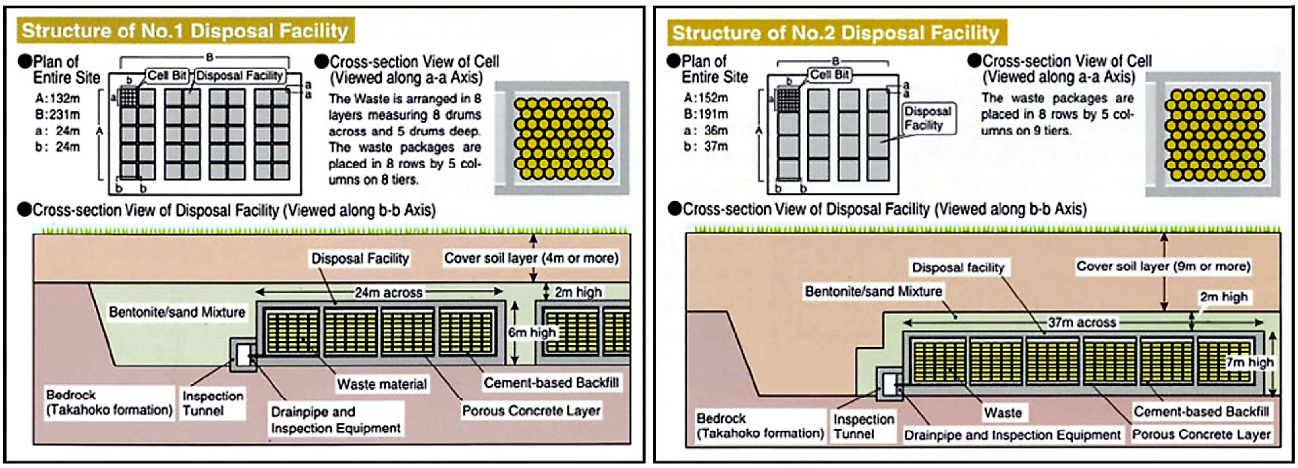

Figure 9: Structure of the Rokkasho-mura LLIW disposal facility (**USDOE, 2011**)

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they are intrusion resistant and, depending on the geological environment of the location, can be perform well, do represent expensive solutions: e.g. they require large initial investment for surface infrastructure (i.e. access ramps, hoists, shafts, ventilation, etc.).

- There are no closed mines in Croatia that are in an appropriate condition to be converted into a repository, especially considering inflow of groundwater, and none of them are in favourable geological environments. Besides, converting an existing mine into a disposal facility is usually a complicated task considering the large number of underground spaces and complicated networks of corridors which reduce the safety of the disposal facility.
- Shallow and deep boreholes are not an appropriate solution for the large volumes of waste under consideration.

Taking these reasons into consideration, it is probable that the future Croatian LILW repository will be either a "surface concrete vault" or a "near surface closed concrete vault" with a "deeper concrete vault" as a less probable option. A deeper concrete vault does provide a significantly higher safety margin, especially considering biological intrusion, however it is more suitable for locations with significantly low groundwater levels. Compared to a near surface closed concrete vault, it is a little more complicated and costly design which has few advantages to make the choice justified.

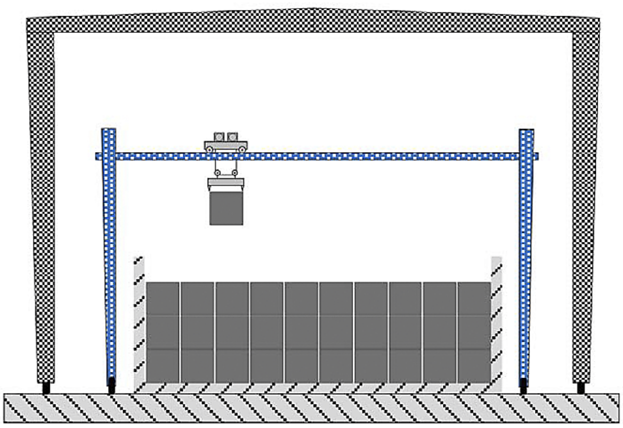

Figure 10: Probable way of filling the vault in the Croatian LILW disposal programme (**ARAO & Fund, 2019**)

As such, a design has been developed here for both types of repositories with a probable form of waste packaging as an initial assumption. The Croatian programme assumes that the conditioned waste will be packed in reinforced concrete containers with approximate dimensions of 2x2x2 m and placed into a reinforced concrete vault, as in **Figure 10** (**ARAO & Fund, 2019**). Different waste packages would not significantly impact the design of the proposed concept.

Taking the probable design of waste packages and cassette for waste packages (vault) for the Croatian programme (**ARAO & Fund, 2019**) and selected concepts for the disposal facility (see **Figure 11**) into consideration, a specific design for the disposal facility, including BSPL and TSPL, is proposed here.

Selection between the two aforementioned concepts will probably be based mostly on the geological environment of the selected disposal site. The surface concrete vault would preferably be used if the groundwater level is nearer to the surface, thus avoiding flooding of the repository in the future if water levels will rise. The near surface closed concrete vault will be less susceptible to erosion and will probably have lesser subsidence, since the properties of the soil at the lower level will be better (more compacted soil at greater depth).

Concrete vaults will probably have dimensions of 6x8x14 m and contain 84 waste packages (7 packages in width, 4 in depth and 3 in height). When the concrete cassette is filled with waste packages, the interspace will be filled with concrete. When the last vault in the repository is filled and closed, the repository will be backfilled – spaces between vaults and left excavated space (for near surface concept) or a space that will give the final shape to the repository (for surface concept). The material used should be a bentonite-sand mixture because it is a pre-prepared material of known and specially selected properties: strength parameters, permeability coefficient, compressibility coefficient, etc. It is advisable to use bentonite clay with a lower percentage of sodium bentonite to avoid excessive amounts of displacement during bentonite swelling as well as the effects of bentonite swelling pressure on BSPL.

3.1. Top and bottom systems of protective layers

The proposed bottom system of protective layers consists of a double set of protective layers. This provides

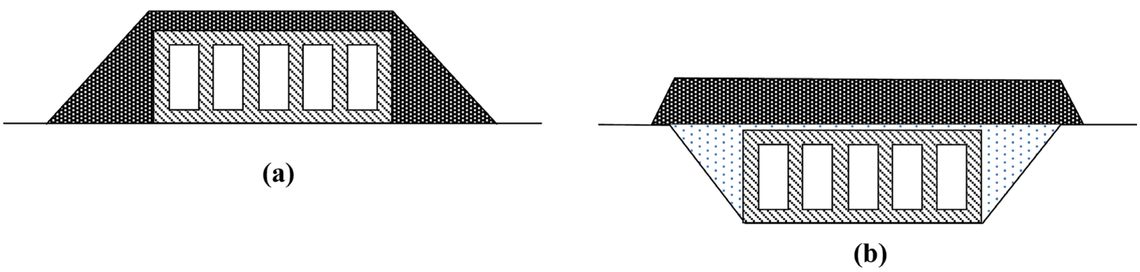

Figure 11: Suggested concepts for Croatian LILW disposal facility: (a) surface concrete vault, and (b) near surface closed concrete vault

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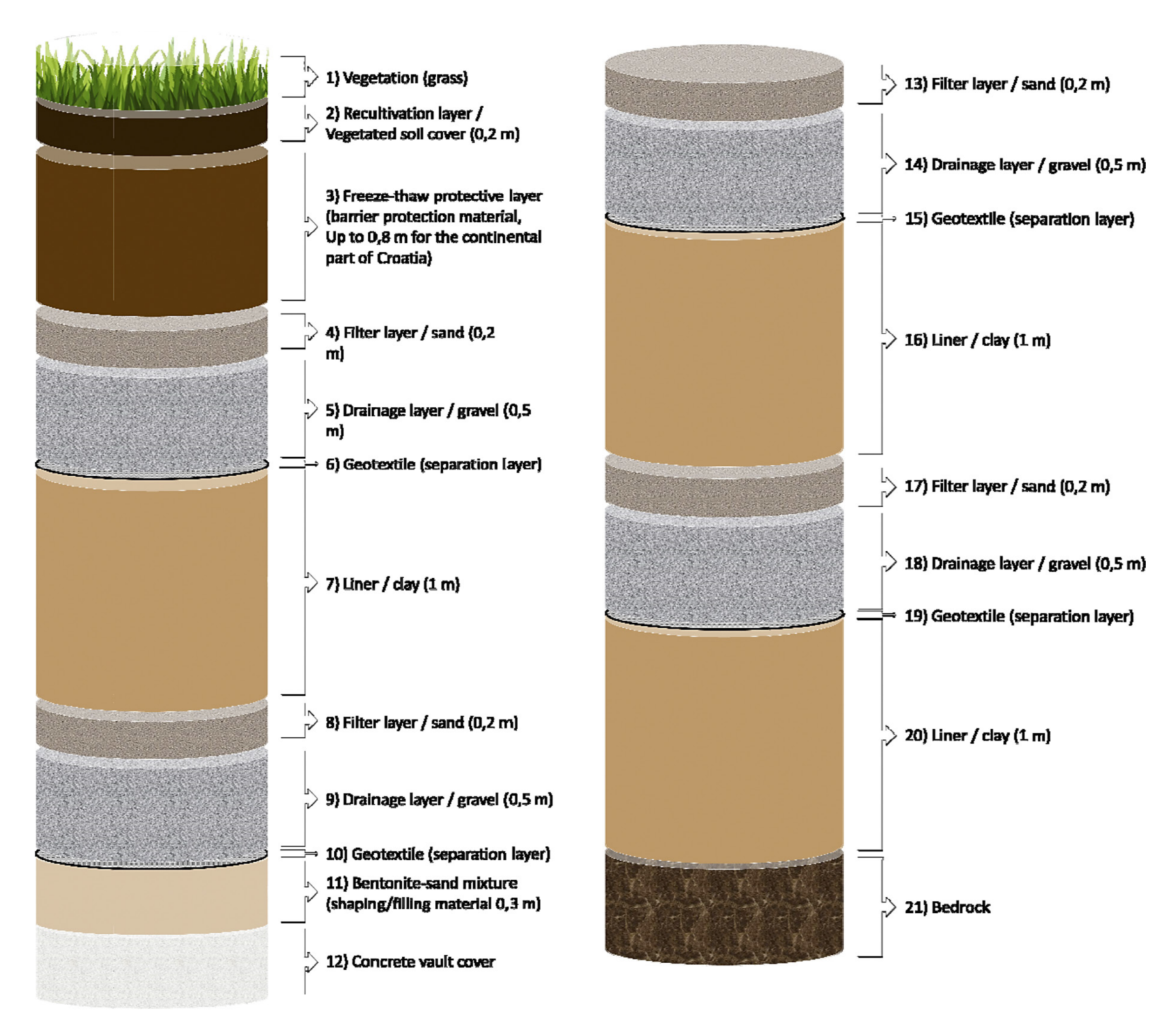

Figure 12: Proposed top (left) and bottom (right) system of protective layers for the Croatian LILW disposal facility

two drainage layers – one (inner) for the leakage detection and primary drainage, and another (outer) as a safety procedure. The idea is applying a double protective system as in the case of landfills of solid municipal waste which are above an important aquifer or as for landfills of hazardous waste. The same principle can be applied for lining materials: one is primary, and one is secondary, in case of leakage. Considering that radioactive waste, especially ILW, is significantly more hazardous than municipal waste, existing experiences with environmental contamination with some types of radioactive waste, and the practical durability of concrete barriers, the price of such a system would be justified. Also, if stakeholder engagement is taken into account, a more serious and permanent system of protective layers would gain greater trust and help the approval of the location as well as the disposal concept more easily.

Waste packages and vaults can be considered as a sufficient barrier, however, if waste packages are transported from a considerable distance (plant for conditioning waste and construction of packages) and if there is significant manipulation with packages (in case of transporting from storage site) it is to be expected that a certain amount of fractures and other damage will appear. Besides, concrete is not a perfect material, and it will undergo deterioration with time. If concrete is exposed to acid rain or any fluid with a pH less than 13, since the concrete system is at equilibrium at pH 13+ to begin, then moves to pH 12.5 as the NaOH and KOH leach out. Then, as the $Ca(OH)_2$ leaches out, the concrete pH will drop to 10-10.5 where it will likely stay until (if) it dissolves completely. So, in effect, any solution with a pH lower than the concrete will cause leaching, the concrete will deteriorate and thus speed up the release of radionuclides.

Between two adjoining protective layers of significantly different material granulation (i.e. drainage (5 in **Figure 12**) and lining material (6 in **Figure 12**)) there should be material which will ensure the separation of

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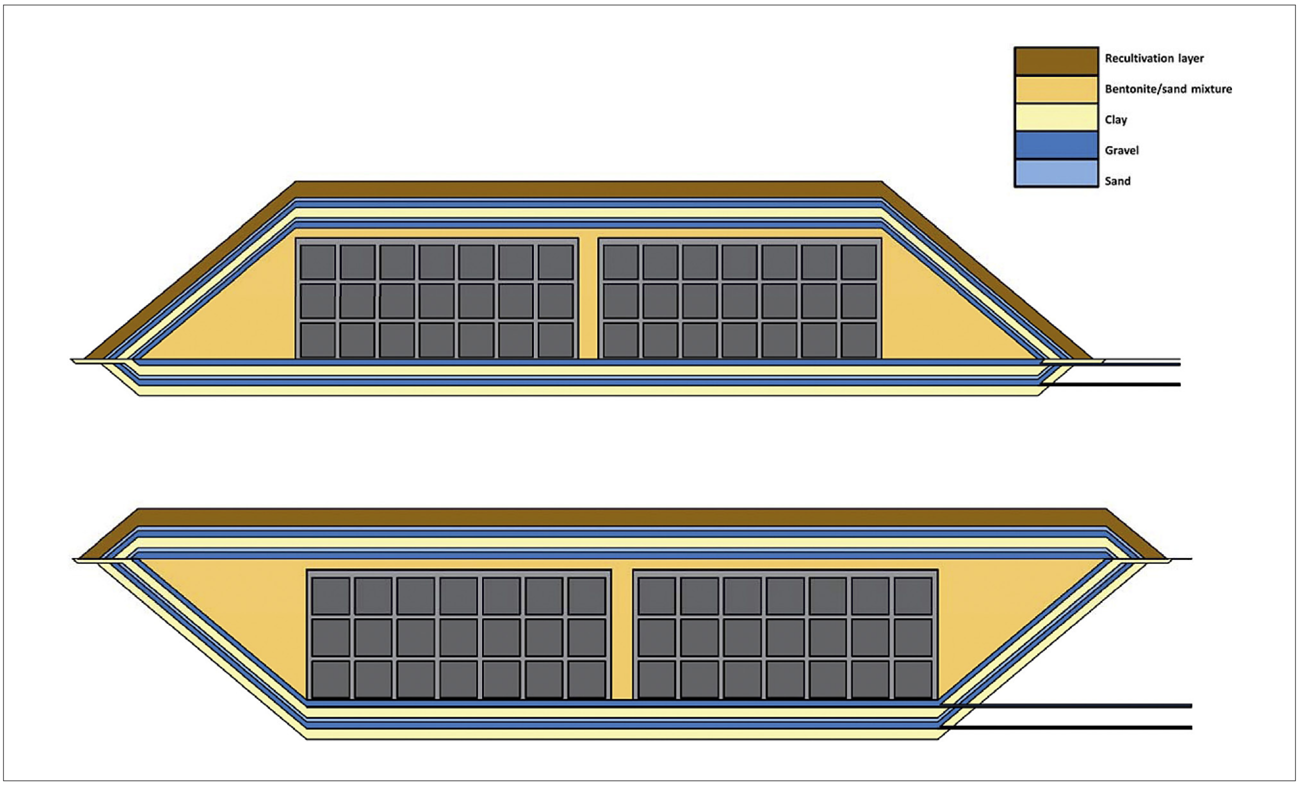

Figure 13: Suggested surface concrete vault (upper), or near surface closed concrete vault (lower) concept for the Croatian LILW disposal facility

soil layers (6 in **Figure 12**). Additionally, there should be some kind of filtration material. If geotextiles are used, they will also provide a certain reinforcement to the structure. However, geotextiles are not as durable as natural mineral materials and so significant deterioration is expected with time. It can be concluded that geosynthetics can be used, but the repository design must not rely strongly on their long-term performance (**Greenwood et al., 2012; GEOFABRICS, 2017**) and it is recommended to use more natural (mineral) materials.

The same logic can be applied to the top system of protective layers, with special consideration for the recultivation layer (vegetative / planting soil, 2 in **Figure 12**) and the freeze-thaw protective layer (barrier protection material, 3 in **Figure 12**).

One of the issues concerning the quality of the lining/sealing materials is gas permeability since there is a possibility that organic/biodegradable waste that has not been incinerated will be present in the canisters and this will produce a certain amount of gas during decomposition. Gas can also be produced in the case of tank corrosion. In this case, it will be necessary to determine the gas permeability of the sealing layers, including the bentonite/sand mixture (**Vučenović et al., 2017a, b, 2021**).

Cross-sections through the suggested systems of protective layers are given in **Figure 12**.

It is proposed that the TSPL consists of:

- A recultivation layer (2) – about 0.2 m of humus, organic soil as a base for vegetation which should minimise erosion and help meteoric water run-off. It also helps integrate the repository into the environment.
- A freeze-thaw protective layer (barrier protection layer) (3) – up to 0.8 m of locally excavated soil. The thickness will vary considering the depth of soil that usually freezes during the winter period. For the continental part of Croatia, it should be 0.6-0.8 m.
- A precipitation collection system – consists of:
  - o a filter layer (4) – 0.2 m of sand,
  - o a drainage layer (5) 0.5 m of gravel.
- A geotextile (6) – separation material which will prevent intermixing of the gravel and clay layers. A geogrid can be used as well.
- A liner (7) – 1 m of clay with a permeability of < 1 x 10^{-9} m/s. If bentonite clay is to be used, special attention should be paid to the swelling of the clay to avoid deformation, especially the rising of the upper layers and the formation of cracks in case the liner begins to lose water (drying and shrinkage).
- Secondary precipitation collection system which should minimize percolation of rainwater into the repository – consists of:
  - o a filter layer (8) – 0.2 m of sand,
  - o a drainage layer (9) – 0.5 m of gravel.
- A geotextile (10) – separation material which will prevent the intermixing of gravel and clay.

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- A shaping/filling material (11) – bentonite-sand mixture whose thickness will be determined during the closing of repository (no more than 0.3 m). This material will be placed directly upon concrete vault cover (12).

It is proposed that the BSPL consists of:

- A leachate collection system – consists of:
  - o a filter layer (13) – 0.2 m of sand
  - o a drainage layer (14) – 0.5 m of gravel. This layer will be the functionality control layer. If any leachate is to be detected it should be evacuated and if it contains radionuclides it has to be decontaminated before release into the environment. Basically, if the TSPL is functioning properly this layer should remain "dry". In this layer there are also drainage pipes that will help drain the leachate if it appears.
- A geotextile (15) – separation material which will prevent intermixing of gravel and clay.
- A liner (16) – 1 m of clay with a permeability f < 1 x 10^{-9} m/s.
- A second, "fail safe" leachate collection system – consists of:
  - o a filter layer (17) – 0.2 m of sand
  - o a drainage layer (18) – 0.5 m of gravel. If leachate is to be detected in this layer, it should be evacuated and if it contains radionuclides, it has to be decontaminated before release into the environment. This layer also contains drainage pipes.
- A geotextile (19) – separation material which will prevent intermixing of the gravel and clay layers.
- A second, "fail safe" liner (19) – 1 m of clay with a permeability of < 1 x 10^{-9} m/s. It is constructed at the bottom of the excavated trench (pit).

3.2. Suggested disposal facility designs

Depending upon the level of the groundwater, type and quality of the local soil (and bedrock) and its geological and geomechanical properties, a surface concrete vault, or near surface closed concrete vault concept could be chosen. Both concepts are shown in **Figure 13**.

The design of the conceptual solution shown in **Figure 13** is somewhat simplified compared to detailed systems of the protective layers shown in **Figure 12**, but the main outlines of the design are included.

4. Discussion

Existing LILW repository concepts rely mainly on the waste packages and the materials (predominantly concrete) for their performance while most of the manufacturers present concrete containers as safe, they always mention the possibility of cracks. The durability of concrete must also be taken into account, especially if the concrete is exposed to filtered rainwater with a pH that will affect concrete.

The main premise of the LILW repository in Croatia is that the repository should perform its safety functions for 300 to 1 000 years or more). However, experience with older repositories and municipal landfill sites is that some of them may be forgotten, especially if they have not been included in maps. For example, it is not unusual that, during the construction of new buildings, an old municipal waste disposal site is discovered. Therefore, relying mainly on the protecting cover and the quality of concrete containers can be insufficient throughout the life of the repository.

Experience gained with designing and monitoring the landfills of municipal waste shows that certain materials and protective layers are not as durable and high-quality as expected, and that in certain situations and under certain effects that will appear over a longer period of time, there may be significant changes in structures and materials. In order to design a long-lasting object with protective systems which will last as long as is required – as long as the radionuclides contained within represent a threat to the biota, it is essential to anticipate possible problems and changes and to bypass them or to assume the best possible materials and methods of installation to create an object whose duration and safety will guarantee the planned performance.

5. Conclusions

The new design of the LILW repository presented in this paper is a significant improvement over existing designs as it offers a more durable system of protective layers. Unlike existing concepts, it relies not only on the protective cover but the bottom system of protective layers which will, in case of radionuclides leaching out of the waste, serve as a system for leachate drainage and radionuclide detection. In addition, the double liner system provides added safety via built-in redundancy.

Planned research and testing of this new design will, in future publications, include:

- Running a safety assessment based on this design;
- Testing of the geometry – slope stability;
- Calculation of the subsidence.

Future research will include a none-to-one comparison of this design and existing repository designs with respect to assessed safety and calculated construction costs, in order to conclude where the new design is a significant improvement over existing designs and to optimise the design to expected Croatian conditions.

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SAŽETAK

Unaprijeđeno idejno rješenje odlagališta nisko i srednje radioaktivnoga otpada

S obzirom na sve veću potrebu za izgradnjom odlagališta nisko i srednje radioaktivnoga otpada u Republici Hrvatskoj u radu se predlaže dizajn odlagališta koji je s geotehničkoga aspekta jednostavan, praktičan i siguran te znatno poboljšan u odnosu na postojeća idejna rješenja. Postojeća odlagališta nisko i srednje radioaktivnog otpada uglavnom su pripovršinske konstrukcije trezorskoga tipa s nekom vrstom pokrovnoga sustava zaštitnih slojeva, međutim većina odlagališta nema donji sustav zaštitnih slojeva, osim betonske podnice (temelja). Razlog ovakva dizajna jest povjerenje u spremnike za otpad koji se uglavnom izrađuju kao armirano-betonske kutije. S obzirom na to da je beton materijal koji će u određenim uvjetima propadati („korozija cementne matrice"), nužno je projektirati odlagalište kako bi se spriječilo bilo kakvo prijevremeno ispuštanje radionuklida. Unaprijeđeni idejni dizajn odlagališta nisko i srednje radioaktivnoga otpada prikazan u ovome radu trebao bi osigurati bolje zadržavanje radionuklida i osigurati dugoročnu sigurnost odlagališta. Članak je prvi u nizu koji obuhvaća osnovni dizajn odlagališta, sustave zaštitnih slojeva i preliminarne analize stabilnosti kosina.

Ključne riječi:
odlagalište, nisko i srednje radioaktivni otpad, dizajn, zaštitni slojevi

Author's contribution

Želimir **Veinović (1)** (Associated professor, PhD, expert for radioactive waste and spent nuclear fuel management and disposal) designed the original idea of the new concept, arrangement of the protective layers, manner of the construction, etc. **Helena Vučenović (2)** (Assistant professor, PhD, expert for the soil mechanics and numerical methods) developed numerical models of the repository and cooperated in protective material selection. **Ivana Rožman (3)** (mag.ing. geol., expertise in numerical modelling) developed the repository design and numerical models of the repository. **Galla Uroić (4)** (mag.ing.min., PhD candidate, expert for radioactive waste and spent nuclear fuel management and disposal) helped in the development of the repository design and material selection.

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