European Partnership on Radioactive Waste Management

Deliverable 7.2 Representative conditions and identification of the key parameters influencing the long-term behaviour of LL-ILW

Work Package L'OPERA

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Executive Summary

EURAD2_WP7 L'OPERA Task 3 aims to identify and evaluate the representative environmental conditions of disposal facilities for the long-term management of low- and intermediate-level waste (LILW). This involves understanding the key parameters that influence the durability and stability of various waste matrices and waste forms and characterising the environmental conditions prevailing in disposal facilities.

The deliverable begins with an introduction **Section 1**, outlining the scope and objectives of L'OPERA and Task 3.

Section 2 provides a concise overview of the radioactive waste disposal strategies employed by partner countries. This summary aids in selecting the appropriate boundary conditions that align with the scope of L'OPERA for assessing the durability of waste forms and waste matrices. **Section 3** outlines waste acceptance criteria in partner countries and their national requirements for the stability of matrices and waste forms relevant to the system being investigated in WP7.

Section 4 summarises the key parameters of waste forms and representative conditions of disposal facilities for the long-term management of LILW to be considered in L'OPERA:

- Section 4.1 emphasises the importance of durability in matrices and waste forms, focusing on properties to be investigated in L'OPERA from the perspectives of chemical, physical, and mechanical properties. This highlights the need for waste forms to resist chemical reactions between waste and matrices, as well as between waste forms and the environment, to prevent radionuclide release. Physical integrity is another critical aspect, with studies assessing factors such as porosity, density, homogeneity, and resistance to structural alterations. Waste forms must withstand environmental conditions, such as temperature fluctuations, humidity, and radiation, over extended periods. Mechanical durability is also crucial, with evaluations focusing on the compressive strength, flexural strength, and resistance to mechanical stress. Ensuring that waste forms retain their structural integrity under anticipated load conditions is essential for long-term containment and confinement.

- Section 4.2 presents the characterised representative conditions of disposal facilities, focusing on key geochemical parameters for leaching tests and long-term environmental conditions for ageing tests. These conditions are critical for understanding how waste forms interact with their surroundings and ensuring their long-term stability. These findings serve as a basis for proposing protocols for Task 5, which focuses on waste form durability and stability testing.

The conclusion, presented in **Section 5**, offers recommendations for defining experimental protocols and procedures. Furthermore, several perspectives for future research are included.

In summary, EURAD-2 WP7 T3 provided valuable insights into the key parameters influencing the long-term behaviour of waste forms and matrices. These findings underscore the importance of chemical, physical, and mechanical stability, as well as the need for standardised protocols and collaborative research to ensure the safe and effective management of radioactive waste.

Keywords

Long-term management, Low and Intermediate Level Waste, Durability, Properties, Matrices and Waste forms, Integrity, Environmental conditions, Disposal facilities.

Table of content

List of figures

List of Tables

Glossary

AAR	Alkali-Aggregate Reaction
ADR	General Requirements for Road Transport
ANDRA	French National Radioactive Waste Management Agency
APC	Polypropylene-reinforced Asphalt Concrete
ASR	Alkali-Silica Reaction
CEMRW	Centralised Radioactive Waste Management Enterprise
CIEMAT	Centre for Energy, Environmental and Technological Research in Spain
CNCAN	Romanian National Commission for Nuclear Activities Control
CNRS-PIMM	French National Scientific Research Centre located in the Process and Engineering in Mechanics and Materials laboratory
COVRA	Dutch Nuclear Waste Processing and Storage Company
CRP	Coordinated Research Project
CS	Compressive Strength
CSA	Aube Disposal Facility, a surface disposal facility in France
CRME	State Specialised Enterprise Centralised Radioactive Waste Management Enterprise
CRME	Engineered Near-Surface Disposal Facility for Solid Radioactive Waste on the Vektor site
DEF	Delayed Ettringite Formation
DFDSMA	Romanian Near-surface Disposal Facility
DNDR	Romanian National Repository Baita Bihor
DSRS	Disused Sealed Radioactive Sources
DU	Depleted Uranium
EBS	Engineered Barrier System
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
ESA	External Sulfite Attack
GDF	Geological Disposal Facility
HLW	High-level Waste
IAEA	International Atomic Energy Agency
ICARUS	Innovative Characterisation Techniques for Large Volumes
ICSRM	Industrial Complex for Solid Radioactive Waste Management at ChNPP
IER	Ion Exchange Resin
IFIN-HH Bucharest	Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering
ILW	Intermediate-level waste

ISIN	National Inspectorate for Nuclear Safety and Radiation Protection, Italy
LLW	Low-level Waste
L'OPERA	Long-term Performance of Waste Matrices
LRSF	Liquid Radioactive Waste Storage Facility
MIP	Mercury Intrusion Porosimetry
MKPC	Magnesium Potassium Phosphate Cement
NORM	Naturally Occurring Radioactive Materials
NRG PALLAS	Dutch Nuclear Research and Isotope Production Company
OPC	Ordinary Portland Cement
ORANO	French Multinational Nuclear Fuel Cycle Corporation
OSPU	Basic Health and Safety Rules for Radiation Protection of Ukraine
PREDIS	Pre-disposal Management of Radioactive Waste, an EU project
RATEN ICN	Institute for Nuclear Research Pitesti, Romania
RH	Relative Humidity
RLOW	Radioactive Liquid Organic Waste
RN	Radioactive Nuclide
ROL	Radioactive Organic Liquids
RSOW	Radioactive Solid Organic Waste
RW	Radioactive Wastes
RWM	Radioactive Waste Management
RWDS	Radioactive Waste Disposal (Storage) Site
SCK CEN	Belgian Nuclear Research Centre
SEM	Scanning Electron Microscopy
SIIEG NASU	National Academy of Sciences of Ukraine
SISPs	State Interregional Specialised Plants
SOGIN	Nuclear Plant Management Company in Italy
STREAM	Sustainable Treatment and Immobilization of Challenging Waste
STUK	Finnish Radiation and Nuclear Safety Authority
SURAO	Radioactive Waste Repository Authority in the Czech Republic
TG	Technical Guide
UJV	ÚJV Řež, a. s.
UNIROMA	Sapienza University of Rome, Italy
UNIPISA	University of Pisa, Italy

VLLW	Very-Low Level Waste
VTT	Technical Research Centre of Finland
WAC	Waste Acceptance Criteria
WP7	Work Package 7 in EURAD2
Short-lived radioactive waste	Radioactive waste with such a level of radioactivity that the exemption from the regulatory control of the state regulatory body can be reached earlier than 300 years
Long-lived radioactive waste	Radioactive waste, which level of exemption from the regulatory control of the state regulatory body will be reached after 300 years
Radioactive waste disposal (burial)	Emplacement of radioactive waste in appropriate facilities intended for radioactive waste management without the intention of retrieval
Radioactive waste storage	Holding of radioactive waste in a facility in which it is provided with isolation from the natural environment, physical protection and radiation monitoring, with the possibility of subsequent removal, processing, transportation and burial
Radiation waste immobilisation	Conversion of radioactive waste into other forms through solidification, embedding in any matrix or encapsulation in a hermetic container
Radioactive waste conditioning	Operations of preparation of radioactive waste for transportation, storage or disposal. The conditioning can be carried out through the emplacement of radioactive waste into containers or its immobilisation
Radioactive waste treatment	Operations intended to ensure the safety or save costs by changing the characteristics of radioactive waste
Radioactive waste processing	Any operation which changes the characteristics of radioactive waste, in particular, previous treatment and conditioning
Radioactive waste management	All activities (including the decommissioning activity) related to handling, pre-treatment, treatment, conditioning, transport, storage or disposal of radioactive waste
Pre-treatment of radioactive waste	Decontamination, collection, and sorting of radioactive waste
Radioactive waste	Materials and substances whose radionuclide activity level or radioactive contamination level does not exceed the limits established by the applicable norms, provided that no further use of these materials and substances is foreseen
Specialised enterprise for radioactive waste management	An enterprise or association which carries out, based on a license, radioactive waste collecting, processing, transporting, storing, and (or) burial
Radioactive waste storage facility	A structure for storage or burial of radioactive waste with the obligatory provision of engineering, geological, natural and other barriers to prevent migration of radionuclides

1. Introduction

EURAD2 WP7 L'OPERA (long-term performance of waste matrices) aims to demonstrate the performance of new matrices under representative disposal conditions. This demonstration will play a crucial role in enhancing and optimising pre-disposal operations. Building on the findings of the previous European PREDIS (Pre-disposal management of radioactive waste) project, L'OPERA intends to conduct a thorough evaluation of the long-term performance, behaviour, and durability of innovative matrices and waste forms used for the immobilisation of low- and intermediate-level waste (LILW).

L'OPERA encompasses four technical tasks: Task 3 (T3) "boundary conditions," Task 4 (T4) "inventory of the conditioned materials and complete characterisation," Task 5 (T5) "waste forms durability and stability testing," and Task 6 (T6) "implementation." Among these, T3 focused on identifying the representative conditions of disposal facilities for the long-term management of LILW. The primary objective is to identify the key parameters that influence the durability and stability of various waste matrices and waste forms and to characterise the environmental conditions prevailing in disposal facilities. The results from T3 are used to set up experimental protocols and procedures for T5 as well as to outline the simulation scenarios for T6. The relationships and interactions between these tasks are illustrated in Figure 1.

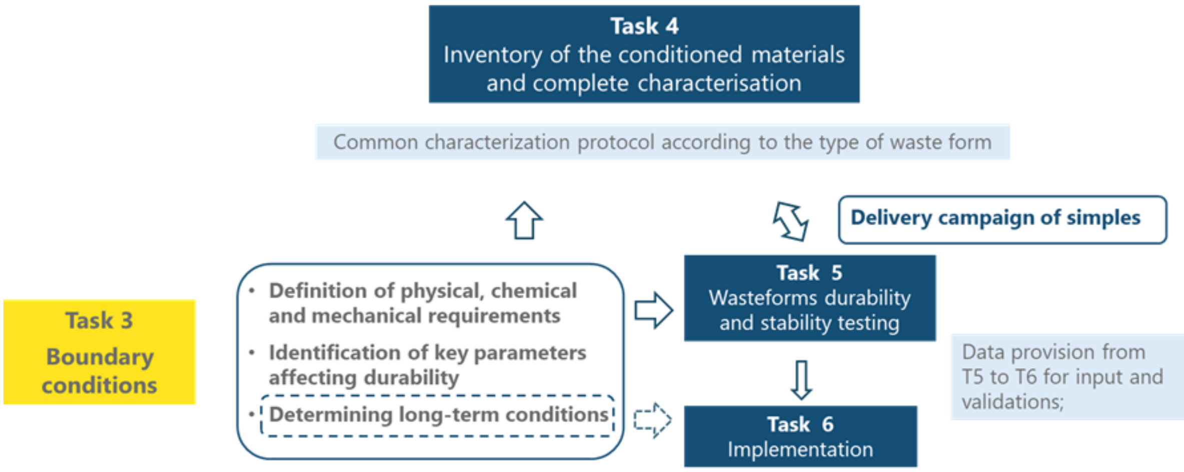

Figure 1: Task interactions in WP7 L'OPERA.

To achieve the objective of T3, a survey was conducted within the task. A copy of the survey questions can be found in Appendix A. The survey included five main questions designed to gather information on the key areas.

(i) Existing national criteria regarding the durability of the investigated matrices and waste forms, as well as the established durability protocols and executed experimental procedures.
(ii) Long-term properties of matrices and waste forms to be investigated in WP7, focusing on chemical, physical, and mechanical properties;
(iii) Key (geo)chemical parameters relevant to the disposal concept associated with the leaching tests to be examined in WP7.
(iv) Relevant long-term environmental conditions related to ageing tests in WP7;
(v) A brief overview of the national storage/disposal facility and national strategy for radioactive waste management (RWM).

The survey was distributed to partners, end-users, and stakeholders involved in WP5 ICARUS (innovative characterisation techniques for large volumes), WP6 STREAM (Sustainable treatment and immobilisation of challenging waste), and WP7 L'OPERA. Responses were collected from 12 countries, including partners from Belgium, the Czech Republic, France, Finland, Italy, Spain, the Netherlands, Ukraine, and Poland, along with end-user feedback. Additionally, responses were received from a

Romanian end-user, an American stakeholder, and a Mexican external participant. This deliverable summarises the survey responses to suggest the boundary conditions for WP7. It includes partner contributions, with additional input from two end users and one stakeholder in the conclusion section, rather than being exclusively presented in other sections.

2. National disposal facilities and strategy for management of LILW

This subsection provides brief descriptions of national storage and disposal facilities, along with the national strategies for RWM in each partner country. The primary objective is to identify the most relevant boundary conditions by considering the specific characteristics of each country's storage and disposal facilities, as well as their overall strategy for managing radioactive waste (RW).

2.1 Strategies for partner countries

BELGIUM

Surface Disposal Facility

The surface disposal program for Category A waste in Dessels is currently in the construction phase. This engineered surface facility can handle short-lived LILW. The key characteristics include the following.

- Designed for approximately 70,000 m³ of conditioned short-lived LILW
- Multi-barrier system consisting mainly of a sand-cement embankment, concrete monoliths, concrete modules, and multilayer cover
- Inspection rooms beneath the modules for leak detection
- 300-year institutional control period after closure
- Soon in construction with operation expected to begin in 2029
- Will accept standardised concrete caissons containing (post-)conditioned waste and backfill mortar (monoliths)

Deep Geological Repository

The current concept for managing high-level waste (HLW) and long-lived LILW in Belgium involves a deep geological repository for poorly indurated clay formations.

The concept includes:

- Repository depth of approximately 200-300 m in poorly indurated clay.
- The supercontainer concept for HLW is designed to provide multiple engineered barriers for the long-term containment of vitrified waste and spent fuel, featuring the following:
    - Carbon steel overpack that provides reducing conditions and containment.
    - A cementitious buffer (OPC) provides alkaline conditions, which passivate metals and minimise corrosion and related gas production.
    - Stainless steel envelope for handling and emplacement.
- The concept of monolith B for LILW is designed to provide structural integrity and radionuclide retention, featuring the following:
    - Concrete container for physical containment and radiation shielding.
    - Mortar immobilisation matrix embedding the conditioned waste (200 L drum or CSDC) to reduce leaching and provide additional radionuclide retention.
    - Concrete lid for complete encapsulation.
- Gallery-based design with horizontal emplacement provides an overall alkaline environment, which passivates metals and minimises corrosion and related gas production.

- Operational timeframe for waste emplacement tentatively set for ~2070-2100
- Currently in the research and development phase
- Safety case developed for a 1 million-year timescale
- Attention is dedicated to waste retrievability, although this condition leads to significant technical difficulties
- EBS works in conjunction with the natural clay barrier

Intermediate depth Disposal for Radium-Bearing Waste

A facility for the intermediate-depth disposal of radium-bearing waste is in the conceptual planning stage. This facility will address the unique challenges posed by radium and its decay products.

- Specialised engineered barriers for radon gas containment
- Currently in conceptual design phase

CZECH REPUBLIC

RWM at the national level is granted by the State organisation SURAO (Radioactive Waste Repository Authority) established by the Ministry of Industry and Trade. SURAO operates three repositories for intermediate-level waste (ILW) and low-level waste (LLW); the facility for the category very low-level waste (VLLW) is not developed, and this waste stream is disposed of together with other categories. The Dukovany repository is dedicated to the LLW category, represented mainly by the operational waste originating during the operation of nuclear power plants (NPPs).

The repository consists of an operating building, two double rows of disposal concrete vaults, access roads, and the surrounding grassed areas. The repository comprises a total of 112 concrete vaults arranged in the form of two double rows with 28 concrete vaults per row. The total area of the disposal concrete vaults is 13,370 m^2, and the volume of the concrete vaults is 55,450 m^3. The repository is designed as a multibarrier system where the concrete vaults were constructed on a concrete slab, the unevenness of which was corrected via the application of a sloping base concrete layer coated with a layer of penetrating paint. This layer was then covered with a layer of polypropylene-reinforced asphalt concrete (APC), a layer of gravel drainage material and a further layer of APC.

The backfill, as concrete with prescribed properties, is delivered by the vault when the capacity of each vault is spent. The facility is equipped with two separate water drainage systems, which have been installed in the backfill areas of each row of concrete vaults. There are a total of four drainage shafts (control shafts).

The expected period of durability and safety cases is 300 years, and the Dukovany repository is a final disposal site where the conditioned RW is disposed of in the geopolymer, bitumen, and cement matrices according to the requirements stipulated in the waste acceptance criteria (WAC) of this facility.

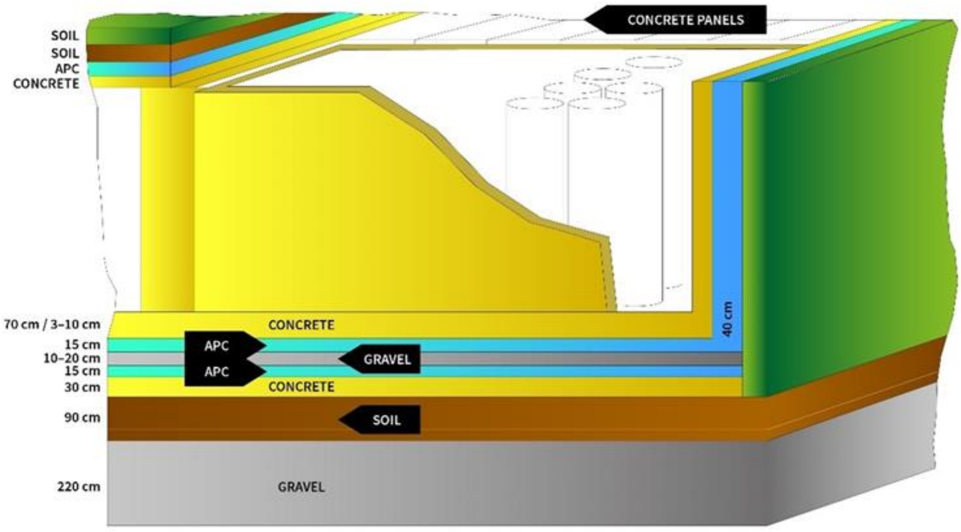

Figure 2: The structure of the Dukovany repository

Figure 3: Disposal of conditioned RW in standard waste packages placed in the disposal vault of the Dukovany repository

FINLAND

Finland's current strategy for the RWM is centred on geological disposal. The Loviisa LILW Repository, operated by Fortum, is situated at a depth of approximately 110 m in crystalline bedrock and has been operational since 1997. Similarly, the Olkiluoto LILW Repository, operated by TVO, is located at a depth of 60–100 m and has been in operation since 1992. Both repositories utilise underground rock vaults for waste containment, incorporating engineered barriers such as cementitious stabilisation and backfill materials.

Future strategies involve expanding the ILW disposal capacity, with additional vaults planned at both Loviisa and Olkiluoto. Finland's deep geological disposal concept for HLW is advancing with the Onkalo Repository operated by Posiva Oy, which is expected to become operational by 2026 at a depth of 400-

430 m. Interim storage is also part of Finland's strategy, with ILW being stored for 20–50 years before final disposal to allow for decay and minimise long-term containment challenges. Finnish regulations require engineered barriers to effectively prevent the release of radioactive substances into the bedrock for several hundred years for short-lived waste and thousands of years for long-lived waste (Y/4/2016). For spent nuclear fuel, the barriers should last for at least 10,000 years (YVL D.5 410a) to ensure that disposal solutions account for long-term geological stability and environmental resilience.

Olkiluoto low-level soft waste is packed in drums, which are pressed to approximately two-thirds of their original volume before disposal. This compaction process reduces the volume of waste, making it easier to handle and store. The ILW, especially resins, is solidified by bituminisation and cementation. These processes involve mixing waste with bitumen or cement to create a stable, solid form that can be safely packed in drums for disposal. The solidification process enhances the structural integrity of the waste, ensuring that it remains contained and degrades at a low rate over time.

FRANCE

France's strategy is based on a set of facilities designed for interim storage (temporary storage of waste until final disposal or treatment if possible) and final disposal facilities. ANDRA (National Radioactive Waste Management Agency) is responsible for long-term RWM in the French territory. ANDRA operates disposal sites and develops projects for disposal facilities

- Surface disposal facility designed for short-lived LILW: CSA, Aube disposal facility in exploitation, and CSM Manche disposal facility closed in 1994.
- CIRES, VLLW disposal
- A project for geological disposal at 500 m depth (Cigéo)
- LILW waste disposal (tens of meters depth)

In the framework of the L'OPERA project, regarding the durability of the new matrix, the surface-disposal CSA is mostly related to.

In CSA, waste packages are disposed of in vaults. Two types of disposal vaults are used in CSA:

- So-called "perishable" metallic waste packages are disposed of in vaults that are backfilled, layer-by-layer, with special concrete.
- Durable waste packages in concrete are disposed of in stacks, and when full, such vaults are backfilled with gravel.

A CSA disposal vault is intended to receive RW packaged in containers that can be very different from one another. These packages may have a cylindrical, cubic, or parallelepiped shape, variable dimensions, and different container compositions ("Concrete" container is qualified as sustainable or durable whilst "metallic" container is considered perishable) and diverse types of emplaced waste (heterogeneous waste, homogeneous waste, steel, concrete, plastic, resin, etc.).

Perishable packages: metallic drums (100, 200, 450, and 870 L) and boxes (5 and 10 m^3, metal ingots from the fusion of metallic waste). Non-perishable packages: 5 m^3 concrete boxes and various types of concrete drums. Waste packages, whether perishable or non-perishable, containing homogeneous or heterogeneous waste, are nearly always grouted inside by mortar. Depending on the type of waste package, the confinement properties are ensured by the matrix or container. The durability of waste packages is expected to last over 300 years during the exploitation and monitoring phases.

The disposal concept developed by ANDRA consists of isolating radioactive materials from the environment for the period required for their radioactive content to decay until the impact of the disposal facility reaches a level comparable to that of naturally occurring radiation (300 years).

To prevent the dispersion of radioactive elements into the environment, the following three barriers have been designed to isolate the waste:

- the waste package into which the waste is embedded within a concrete, polymer, or bitumen matrix.
- the disposal structures, the network of underground galleries and the final capping.
- the geological environment of the site: An impermeable clay layer covered by a draining layer of sand (on which the disposal structures are built) constitutes a natural barrier to protect the environment in case of releases of radioactive elements towards the groundwater table.

Waste packages and disposal vaults ensure the safety of the disposal facility during the operational and monitoring phases (over 300 years). Beyond the monitoring phase, with the arrangements made during the operational phase (e.g., limitation of the quantity of harmful substances in the waste), it is conservatively retained that only the geological medium will contribute to the safety of the facility.

ITALY

Currently, RW is temporarily stored at different sites because of the unavailability of a National Repository. The reference interim storage repository should be designed, constructed, and operated according to ISIN TG n. 30 [1], which collects objectives, criteria, and general safety and radiation protection requirements for the design, construction, operation, and decommissioning of temporary storage facilities for radioactive waste and irradiated fuel [2].

The Italian National Strategy for RWM will consider a near-surface repository with four levels of engineered barrier system (EBS), ensuring durability and safety for 300 years. It will include:

- A disposal facility for VLLW and LLW.
- A long-term storage facility for ILW and HLW.
- The disposal facility is characterised by a system of engineering and natural barriers, disposed in series, which guarantees the containment of radioactivity for 300 years. The engineering barriers will be subject to specific qualification activities, and the natural barriers will be those of the site identified based on specific siting criteria.

The disposal facility, based on the current conceptual model, consists of 90 reinforced concrete cells containing large special concrete modules that enclose metallic containers (cylindrical and prismatic) with conditioned radioactive waste. Around 84,000 m^3 of VLLW and LLW packages will be disposed of. Once filled, the cells will be covered with a multi-layer covering made of inert and impermeable materials.

The near-surface disposal facility consists of:

- Waste packages (first barrier).
- Special reinforced concrete modules (second barrier).
- Reinforced concrete cells (third barrier).
- A multilayered final cover (external barrier) to isolate from the biosphere and prevent water infiltration, drain rainwater, isolate waste, and improve visual impact.

A separate area will house buildings for the long-term storage of ILW and HLW (~14,000 m^3 of packages) before final disposal in a geological repository.

NETHERLANDS

The Netherlands has a policy of long-term interim storage for at least 100 years after the shutdown of the last NPP. Currently, final disposal is not foreseen before 2130 [3], although recent developments in new nuclear builds may change this policy [4]. In late 2024, COVRA published an updated conditional safety case for a geological disposal facility for RW in the Netherlands based on the COPERA program [5], which follows from the OPERA program [6]. This safety case is termed ‘conditional’ as it is recognised that, for eventual implementation of a geological disposal facility (GDF), various parameters will need to be updated, especially to match site-specific conditions, the evolution of the GDF design and the exact waste inventory at the time of implementation. It is assumed that site-specific safety cases will not be required until 2050 [7].

Two separate conditional safety cases were developed and released in 2024: a Clay Safety Case [7] and a Salt Safety Case [8]. The clay safety case considers two conceptual designs, whereas the salt safety case considers a single conceptual design. All these conceptual designs are dimensioned to contain the expected waste inventory that will arise over the next few decades in the Netherlands, including the currently envisaged increase in nuclear power. Conceptual designs separate the disposal of HLW, LILW and Depleted uranium (DU). An example of this conceptual design is shown in Figure 4.

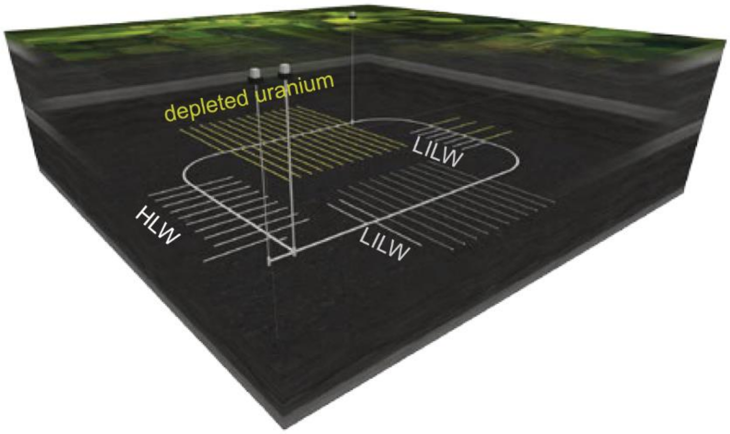

Figure 4: One of the conceptual GDF designs investigated in the Dutch COPERA study [7].

Apart from very low-level naturally occurring radioactive material (NORM) wastes that can be disposed of in conventional landfills in the Netherlands, three radioactive waste categories are distinguished [3]:

- HLW,
- LILW (including NORM waste), and
- Short-lived RW.

Short-lived RW is currently stored in COVRA and is expected to be cleared and disposed of as non-radioactive waste before a repository is operational. Both HLW and LILW are expected to be stored in GDF. Some of the special LILW waste forms in the Netherlands are described in Appendix B. For the very low-level NORM disposed of in landfills, the same WAC applies as for the other (non-radioactive) wastes. Among others, very stringent requirements for leaching characteristics are applied to these landfills.

The COPERA safety case considers three waste scenarios for the total inventory of radioactive waste to be disposed of in the repository: waste scenario 1 is similar to the waste scenario considered in the OPERA safety case and the current situation in the Netherlands, Waste scenario 2 expands waste scenario 1 by the extended operation of the Borssele nuclear power plant by 10 years, while waste scenario 3 expands the total inventory of RW by two new nuclear power plants [7]. An overview of the expected waste packages based on waste scenario 1 is shown in Figure 5.

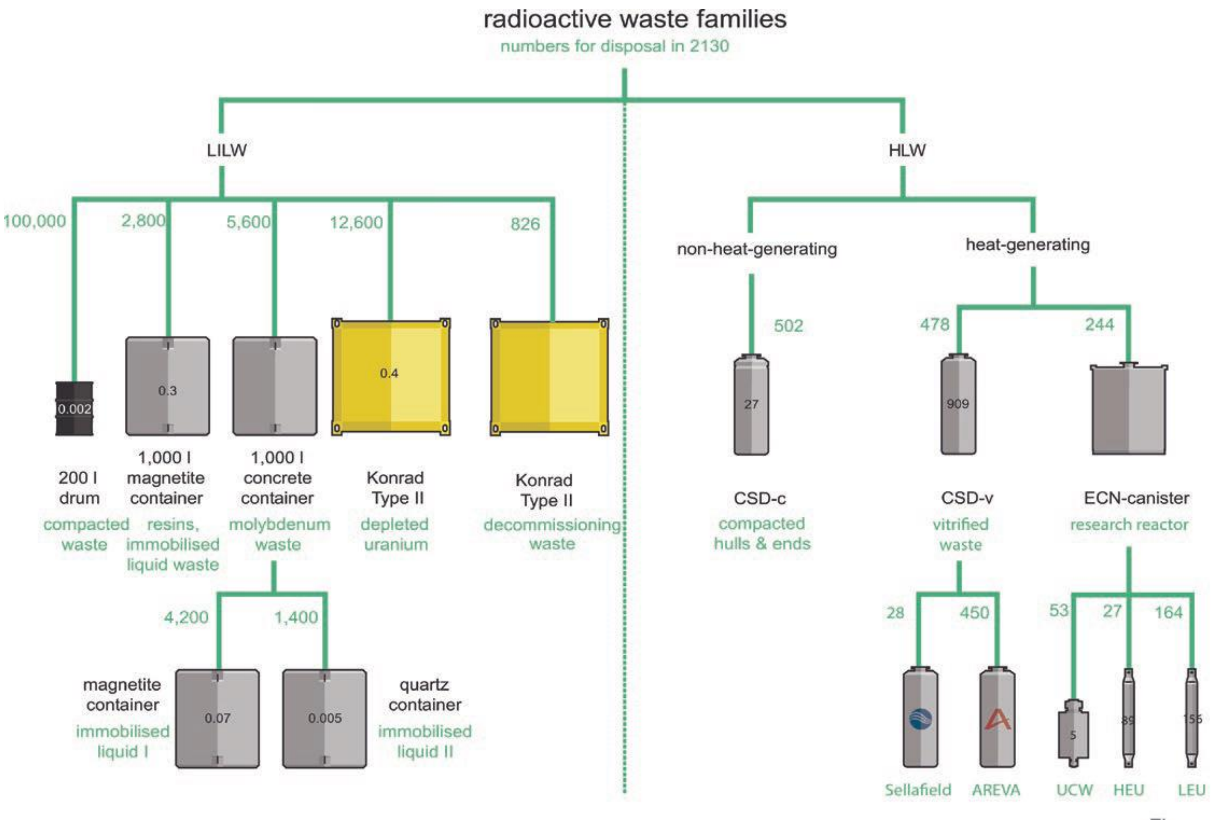

Figure 5: Foreseen waste packages for the Dutch GDF, based on Waste scenario 1 [8].

It is important to note that the current conditional safety cases, as well as the safety cases developed in the OPERA programme, consider instant mobilisation of radionuclides after closure of the repository for LILW, and instant mobilisation of radionuclides at 1000 years after closure of the repository for HLW; that is, the solidified waste form itself is conservatively not treated as a safety barrier [7], [8].

All RW in the Netherlands are interim stored at the national interim storage facility COVRA. The Netherlands follows a dual-track policy: on the one hand, national solutions are investigated; on the other hand, a multinational, regional solution with other European “smaller” nuclear countries [9] is not excluded. In the latter case, no disposal concept is currently being developed. With respect to the national solution, a single geological disposal of all long-living RW is foreseen. Two host rocks are currently under investigation: rock salt and nonindurated clay.

A variety of waste forms are expected to be disposed of in geologic disposal, including approximately 58,070 m^3 of (unconditioned) depleted uranium, 35,275 m^3 of (processed) LILW, including decommissioning waste, and 530 m^3 non-heat generation HLW [8]. The chemical composition of different waste fractions is summarised in [10], [11]. Additional analyses of their degradation behaviour can be found in [10], [12]. Currently, a large volume of LILW waste is cemented in concrete/metal containers [7], [13].

Since neither the host rock nor a specific site for geological disposal has been selected yet, concrete numbers on the expected temperature and pressure evolution and the porosity of EBS and host rock cannot be given. To avoid erosion by deep erosion channels during glacial periods, a minimum depth of 500 m is envisaged [14]. For disposal in clay, suitable layers are identified between 300 and 600 m [4]. For disposal in rock salt, in [15], a depth of the facility between 750 and 850 m is assumed, and depths up to 900 m in [16]. The package sizes and weights are elaborated in [10], [11]. No specific data can be provided for waste homogeneity. Similarly, the physical conditions under which disposal occurs remain unknown. For safety evaluations, a wide range of conditions is usually considered. Therefore, in the current stage, it is expected that the requirements will be covered by the range of conditions provided by other parties.

Various waste packages are currently being considered for the final disposal of different waste fractions [10], [11]. No specific requirements for mechanical properties have been defined. Considering that it is unlikely that the waste will be stored in the vicinity of the current interim storage facility COVRA, it is assumed that the mechanical properties of the waste forms and packages should at least fulfil the general requirements for road transport (ADR). No requirement has been defined for corrosion resistance, but a minimum period for waste package integrity might be defined from the requirements for waste retrieval during the operational phase [6]. Defining requirements on mechanical properties would involve a more in-depth analysis of the evolution of disposal facilities in altered scenarios, as in the normal evolution scenario, in rock salt, the waste would remain dry [17]. In Boom Clay, the radionuclides that would be released from ILW are insignificant compared to the ^{129}I and ^{79}Se released from (vitrified) spent fuel, even considering the instant failure of the ILW waste packages and instant dissolution [18].

POLAND

According to the IAEA classification, the National Radioactive Waste Repository is a near-surface repository dedicated to short-lived, low-, and intermediate-activity (in which the half-life period of isotopes is less than 30 years) RW disposal and sealed radioactive sources. It is also used to store, for an interim period, long-lived, mainly alpha RW, which is ready to be placed in a deep repository. The Rozan repository has been in operation since 1961 and is the only such facility in Poland.

Detailed information on the requirements for the repository is defined in the Decree of the Council of Ministers on 14 December 2015, on radioactive waste and spent nuclear fuel (item 2267).

ROMANIA

In Romania, RW generated by non-energetic nuclear applications (so-called institutional RW) is disposed of in DNDR, a near-surface disposal facility located in the Apuseni Mountains, in a disused uranium exploration mine (in operation since 1985 and refurbished during 2010-2011). The Short-lived institutional RW (including sealed spent radioactive sources) is processed by the waste treatment facilities of two research institutes: the Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH Bucharest) and the Institute for Nuclear Research Pitesti (RATEN ICN). The Long-lived institutional waste is stored (in raw forms) in dedicated storage facilities located at the sites of the two research institutes. The currently used conditioning matrices are cement-based (CEM II type cement) and bitumen, and the disposal packages are standard 200 L and 400 L drums.

The RW generated by the Cernavoda NPP operation is currently stored on-site (in raw forms and only volume reduction, such as incineration and compaction, is currently applied) in dedicated on-site storage facilities for short-lived LILW and long-lived waste in Romania [19].

For the short-lived LILW generated by Cernavoda NPP operation, refurbishment, and decommissioning, the Romanian strategy[20] foresees the construction of a near-surface, multi-barrier disposal facility in the proximity of Cernavoda NPP (to be commenced in 2028).

SPAIN

Spain currently has two RW repositories, one for LLW and one for VLLW. The repositories are co-located at the El Cabril disposal facility. Under the Spanish policy, each great generator (for example, NPPs) is responsible for its waste, including treatment and conditioning according to ENRESA's specifications, until it is accepted for transport to El Cabril. Waste streams that are not accepted for disposal are kept in interim storage on-site until a decision is made about the most adequate treatment or conditioning process.

ENRESA is responsible for developing the El Cabril WAC and applying Quality Assurance to the waste received for disposal. It also conducts pre-transport inspections of waste packages, is responsible for the transport, and accepts responsibility for the waste at the time of transport to El Cabril.

The following list summarises key aspects and performance objectives of the El Cabril site:

- Waste accepted: Short-lived LLW with small quantities of alpha emitters and beta-gamma emitters with a half-life greater than 30 years.
- Facility design: Above ground engineered concrete Vaults.
- Facility capacity: About 40,000 m^3 of conditioned waste.

The following list summarises key performance objectives of the El Cabril site:

- Dose to public: 0.1 mSv/y
- Risk: 10^{-6}/y
- Safety assessment timeframe: Human intrusion agricultural scenarios are 500 years, and all other scenarios are 300 years.
- Institutional control period: 300 years.

Description of the Engineered Barrier System of the LILW Disposal Vaults [21].

El Cabril is a vault-type surface-disposal facility. The scheme illustrated in Figure 6 below summarises the structure of the EBS of El Cabril facility.

Waste packages (mainly 0.22 m^3 drums and 1,3 m^3 metal boxes) delivered by the producers are reconditioned in concrete containers to produce an 11 m^3 final package or disposal unit, which constitutes the first barrier. The internal volume of the concrete container may be backfilled with mortar grout or used to condition institutional liquid waste or contaminated ashes. These packages are placed inside 24x20x10 m concrete vaults. Once the vault is completed with 320 11-m^3 concrete containers, it is backfilled with gravel and a closing slab is built and coated with an impervious painting.

Regarding materials of the EBS, it is a typical cement-based confinement system. CEM I 42,5 R/SR is the base OPC formulation used for the manufacturing of containers and the backfill and sealing mortars, with different additions depending on the functional requirements (superplasticisers, fly ash..). For the impermeabilisation of the vault system, asphalt-based materials and HDPE geotextile sheets were used.

After the closure of the disposal vaults, it is foreseen the construction of an engineered cover system consisting of the superposition of several layers of sand, gravel, clay and HDPE geotextile. This cover system will limit the infiltration of water and will retard the migration of radionuclides into the biosphere in case of failure of the EBS [22].

In the framework of EURAD-2, it is expected that results from SUDOKU will aid in reassessing the impact of the covers and the chemo-mechanical degradation of the vaults on the chemical evolution of the near field.

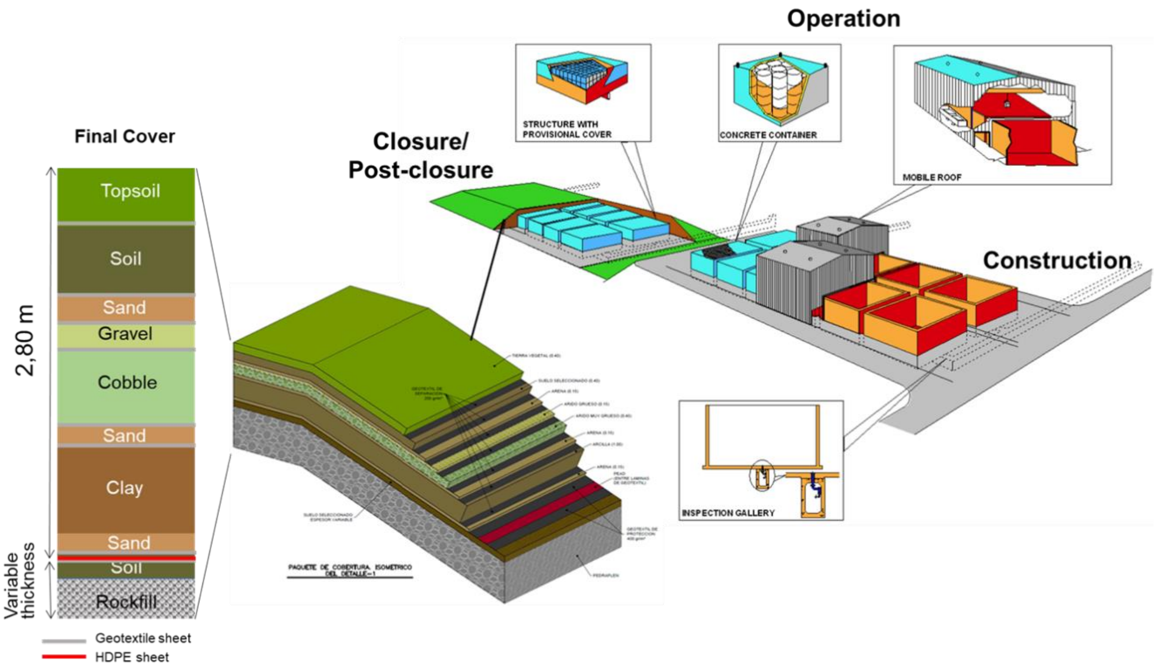

Figure 6: Schematic structure of the Engineered Barrier System of El Cabril facility.

UKRAINE

The RWM system in Ukraine is centralised. To implement the activities of the RWM system in the exclusion zone established in the Strategy for RWM, the Centralised Radioactive Waste Management Enterprise (CEMRW) was appointed as the only operating organisation at all lifecycle stages of the radioactive waste disposal facilities. The Link to the CEMRW (https://www.cemrw.com).

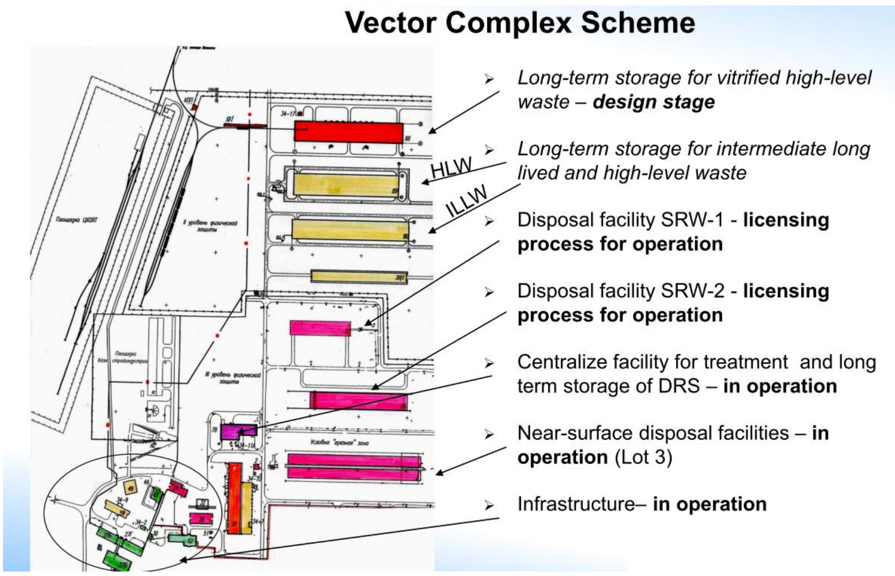

Figure 7: Vector complex scheme.

Figure 8: Engineered Near-Surface Disposal Facility (Lot 3).

The disposal facility's capacity is 71280 m^3, and the volume of the RW packages is 50210 m^3. Lot 3 (Figure 8) has been designed for low—and intermediate-level, short-lived, conditioned RW from ChNPP. The operational period (filling of the disposal facility) is 30 years.

State Interregional Specialised Plants (SISPs) operate in Ukrainian territory (Kyiv, Kharkiv, Dnipropetrovsk, L'viv, Odesa). The exceptional facilities of the Radon Ukrainian State Corporation deal mainly with non-fuel cycle waste and perform the following types of operations:

- storage of liquid and solid waste and spent ionising radiation sources from industrial, medical, and scientific institutions;
- transportation from their collection and temporary storage places in the mentioned organisations.

Table 1 and Table 2 lists the RW stored at the Chornobyl NPP Site and UkrDO Radon SISPs.

Radon Ukrainian State Corporation operates trench-type storage facilities for solid radioactive waste, well-type storage facilities for ionising radiation sources, and tank-type storage facilities for liquid waste. Previously, the Radon Ukrainian State Corporation only accepted waste for storage.

Table 1: Information on Radioactive Waste in Storage at the Chornobyl NPP Site.

Radwaste material	Location	Volume, m^3	Mass, t	Activity, Bq	Main radionuclides
Low-level solid radwaste	SRSF	1069.00	-	1.1E+11	Mixture of nuclides: Cs, Sr, Co, Pu, Am
Intermediate-level solid radwaste	SRSF	926.50	-	4.11E+12	-//-
High-level solid radwaste	SRSF	506.93	-	1.2816E+14	-//-

Table 2: Information on Radioactive Waste Stored at UkrDO Radon SISPs.

Waste material	Location	Volume m^3	Mass, t	Activity, Bq	Main radionuclides
Low- and intermediate-level solid radwaste	Kyiv SISP	2105.0	2493.3	2.92E+15	Cs-137, Ra-226, C-14, H-3,Th-232
	Dnipropetrovsk SISP	591.5	935.5	5.95E+11	Cs-137, Pu-239, Ra-226, U-238+U-235
	Odessa SISP	525.6	343.8	1.66E+13	Cs-137, Kr-85, Ra-226, U-238+U-235
	Lviv SISP	698.2	730.6	5.69E+12	C-14, H-3, U-238+U-235
	Kharkiv SISP	2122.6	091.7	5.93E+12	H-3, Cs-137, Tc-99, Ra-226

2.2 Common features and strategies

Based on the information in Section 2.1, most partner countries have developed plans to dispose of LILW at (near-)surface or intermediate-depth disposal facilities. These plans are tailored to each country's specific disposal concept and aim to ensure the durability and safety of waste containment for an expected period of 300 years. Most partner countries consider (near-)surface disposal facilities or intermediate-depth disposal facilities for interim storage, while the Czech Republic uses the Dukovany repository for the final disposal of ILW. Belgium is currently in the process of constructing a surface disposal facility specifically for short-lived LILW. In Italy, RW is temporarily stored at various sites because of the absence of a National Repository, with a near-surface interim storage repository in the design phase. In the Netherlands, short-lived LILW is currently stored at the national interim storage facility COVRA for at least 100 years, and is expected to be cleared and disposed of in a GDF that is currently being designed.

Each country employs a different EBS to isolate radioactive materials from the environment for the required period. These systems typically feature a multibarrier approach, including waste packages and multi-layered disposal vaults that incorporate cementitious materials and underground rock. These engineered barriers, combined with the natural geological environmental barriers provided by the host rock, create a robust containment system. In most partner countries, LILW is solidified through cementation, while some countries use bituminisation. The Czech Republic takes an additional step by accepting waste conditioned in geopolymer. The solidification process involves mixing the waste with a conditioning matrix to form a stable, solid material that can be safely packed in drums for disposal. In some countries, waste packages are internally grouted with cementitious materials such as mortar. Depending on the type of waste, these packages are reconditioned into concrete or metallic containers.

The incorporation of cementitious materials in EBS highlights the critical need to thoroughly evaluate and assess the durability of waste forms and matrices when exposed to cementitious pore solutions. This assessment is essential because the specific conditions of the solution can greatly influence the long-term performance of the materials, especially over an anticipated period of 300 years. These prioritised parameters are fundamental in establishing experimental procedures in T5, such as leaching tests, and in defining simulation scenarios in T6.

3. Waste acceptance criteria and national requirements

3.1 WAC specification in partner countries

Waste acceptance criteria (WAC) are specific guidelines that determine which types of waste can be accepted at different disposal facilities. These criteria vary significantly depending on the country and the type of disposal facility in question. Each country establishes its own WAC based on national regulations, safety standards, and environmental policies. According to the WAC, essential guidelines have been established to ensure the safe and effective management of radioactive waste. Regardless of the type of disposal facilities, these guidelines specify the radiological, mechanical, physical, chemical, and biological characteristics that waste must meet to be accepted by processing, storage, or disposal facilities. However, there are no specific WACs for long-term durability in most countries.

Table 3: List of parameters and requirements included in WAC.

Country	Only solid/solidified RW	Mechanical stability	Homogeneity	Dose-rate	Surface contamination	Alpha specific activity	Beta/gamma spec. activity	Fissile element mass	Radiation & thermal & chemical stability	Package (damage, weight, type)	Physically hazardous materials: flammable, explosive, aggressive	Putrescence, fermenting, infectious	Void space	Built-up pressure in RW	Gas generation	Heat generation	Organic content	Chemo-toxic waste	RW swelling	Free liquids	Reactive (electropositive) metals	Chelating/complexing agent	Leaching	Passport/labelling
Belgium*	+	+		+	+	+	+	+		+	+	o			+	+	+		+	o	+	+		+
Czech Republic	+			+	+	+	+	+	+	+	+	+			+			+		+		+	+	+
Finland**	+										+			+				+			+			+
France		+	+	+	+	+	+	+		+	+	o									+			+
Italy*	+	+		+		+	+		+	+	o	o	+				+			+	o	+	+	+
Netherlands##	+	+		+	+	+	+	+	+	+	+	+	+		+		+	+		+		+		+
Romania###	+	+	+	+	+	+	+	o	+	+	o				+					+				+
Romania*	+	+		+	+	+	+			+	o	o	+		+	+		+			+	+		
Spain	+			+	+	+	+			+	o	o	+	o	o		+	o		o	o	o		+
Ukraine		+	+	+	+	+	+	+	+	+	+	+	+		+	+	+	+		+		+	+	+

*General/preliminary criteria, will be updated with the commissioning of a disposal facility

**WAC valid for FORTUM disposal facility

#Moldova has defined WAC, Generic WAC, WAC for DSRS packages

##WAC for long term storage

###WAC for institutional waste repository Baita Bihor

o – Banned item

Table 3 details the parameters and requirements included in the WAC for partner countries. Generally, the WAC of most countries addresses the physico-chemical characteristics of the wastes and waste forms. This includes targeting waste solidification, restricting the presence of aggressive chemicals and putrescible materials, limiting the risk of hazards and specific activity of radionuclides, and requiring stability in mechanical, radiation, thermal, and chemical properties. Additionally, the WAC demands performance in leaching and requests the standardisation of waste packages. To be more specific, several key aspects include:

- Waste Solidification: Ensuring that the waste is solidified to prevent leakage and facilitate safe handling and disposal.
- Restriction of Aggressive Chemicals and Putrescible Materials: Limiting the presence of substances that can cause chemical reactions or decomposition, which might lead to the release of hazardous materials.

- Limiting the Risk of Hazards and Specific Activity of Radionuclides: Controlling the levels of radioactivity and other hazardous properties to minimise potential risks to human health and the environment.
- Stability requirements: This ensures that the waste remains stable from the perspective of mechanical, radiation, thermal, and chemical properties under various conditions. This stability is crucial to prevent the release of contaminants over time.
- Performance in Leaching: Evaluating how well the waste resists leaching, which is the process by which water or other liquids can dissolve and carry away contaminants from the waste.
- Standardisation of waste packaging: Requiring that waste packages meet certain standards to ensure consistency, safety, and ease of handling during transportation, storage, and disposal.

By adhering to these criteria, waste management facilities can ensure that radioactive waste is handled, processed, and disposed of appropriately.

3.2 National requirements for the stability of matrix and waste forms

An overview of the existing national requirements and criteria for the stability of matrices and waste forms relevant to the system being investigated in WP7 is provided in this subsection. The matrices under study in WP7 include geopolymer, magnesium potassium phosphate cement (MKPC), Nochar, and alkali-activated materials for the immobilisation of radioactive liquid organic waste (RLOW), such as oil, radioactive solid organic waste (RSOW), such as ion exchange resin (IER), and metallic materials. While most partner countries have established WAC for cementation, the Czech Republic has updated its WAC for geopolymer matrices and conditioned RW of spent resin and sludge.

BELGIUM

Belgium has established a formal WAC for surface disposal facilities, primarily managed by ONDRAF/NIRAS. The current criteria include the following.

Chemical Requirements such as:

- The presence of complex- and chelating-forming agents should be limited
- Limits on the amount of cellulose (complexing agent) that could enhance radionuclide mobility
- No metal that can dissolve in the backfill mortar and release H_2 in an excessive manner
- Chemical compatibility with concrete barriers:
  - Limits on chloride (corrosion of rebars and complexing agent)
  - Limits on sulfate (degradation of concrete barriers)

Physical Requirements such as:

- No expansive process (ASR/DEF) in waste, immobilisation matrix, or waste form
- No free liquid in monoliths

The long-term management of LILW, as outlined for Belgium, underscores the critical need for robust waste form stability and compatibility with disposal environments. For surface disposal, Belgium's stringent WAC, managed by ONDRAF/NIRAS, emphasises chemical stability (e.g., limiting complexing agents, chlorides, and sulfates), physical integrity (e.g., no expansive processes or free liquids), and mechanical performance to ensure safe containment within concrete-based multi-barrier systems.

CZECH REPUBLIC

The requirements for waste forms or conditioned RW in the waste packages are defined in WAC developed based on the Safety Assessment, specifically defined for each of the operated disposal facilities in the Czech Republic. In general, there is a criterion to dispose of only the solid or solidified waste with no presence of free liquids. Additionally, the waste must not contain combustible, flammable, gas-generating, corrosive, or complexing agents, nor any substances that could cause microbial decomposition.

The Dukovany operated disposal facility, dedicated to the disposal of operational waste from NPPs, has been in operation since 1995. During its operational period, the Safety Assessment has been periodically reassessed. As part of a continuous improvement process and in response to changes in legislation, WAC have been updated. Initially, requirements were defined for solidified RW in a cement or bitumen matrix. In 2005, an updated Safety Assessment was developed (see Appendix C (I)), and new WAC were derived, including requirements for waste solidified in a geopolymer matrix (more generally referred to as an aluminosilicate matrix). The following properties are required:

- Max. value of leachability (137Cs and 60Co, 24h test)
- Requirement on compressible strength of the matrix and conditioned RW
- Activity limits for radioactive nuclide (RN) content in waste packages with RW
- Max. value of waste package weight
- Max. equivalent dose rate value on the waste package surface
- Requirements on the waste package size (volume), definition of standard waste packages

FINLAND

The national requirements for the cementation of LILW are outlined below. According to the Finnish Radiation and Nuclear Safety Authority (STUK) regulations, waste must be immobilised, solidified, and structurally sound for disposal. To ensure that waste forms maintain their integrity and containment function over the required period, specific requirements for waste forms were defined.

From a chemical perspective, the requirements for waste forms cover:

- Dissolution of mineralogical phases
- Leaching behaviour/radionuclide leaching
- Compatibility with groundwater chemistry
- No breaking during a 7-day immersion in water
- Curing for 28 days before disposal

In addition to testing for authority approval, suppliers must pretest the cement (as a conditioning material) for long-term safety. The program must include testing for the alkali-aggregate reaction (AAR), delayed ettringite formation (DEF), external sulfite attack (ESA), thaumasite sulfite reaction, and carbonation.

From a physical perspective, the requirements include:

- Diffusion coefficient of the matrix
- Homogenization of the waste
- Absence of air bubbles inside waste forms
- No significant changes in porosity or homogeneity before disposal

Regarding mechanical properties, waste forms must:

- Reach a certain compressive strength after 28 days
- Retain the structural loading
- Withstand repository conditions, such as stress from geological overburden, hydrostatic pressure, and potential seismic activities.

To ensure compliance, durability protocols include laboratory tests and long-term ageing simulations. The performance of the waste forms was assessed under Finnish disposal conditions to evaluate their performance integrity over time.

FRANCE

For Aube disposal facility (CSA), a surface disposal facility, the WAC includes radiological (mass activity radionuclide by radionuclide, criticity…), chemical (inventory of toxic species, chelating species, stability of the waste (list of forbidden materials such as free liquids, evaluation of gas production, fire properties, swelling, etc.), and mechanical parameters (compression resistance, drop resistance, etc.). Waste confinement should be assured for 300 years by the waste package/waste, which means that the waste/package/waste should not be degraded during this period.

In the specific case of RLOW, it is temporarily stored at different sites awaiting treatment and elimination. The French reference process for Radioactive Organic Liquids (ROL) (oils, solvents, etc.) is incineration in the facility (Cyclife). However, some oils and organic liquids from all types of sites (operation, maintenance, and dismantling) are not compatible with the acceptance specifications of this channel due to their chemical composition (chlorides and fluorinated compounds) and/or their activity (α activity > 370 Bq/g). As an alternative to handle this kind of waste, waste producers have developed a new process of encapsulation with new matrices, such as Nochar by ORANO. An exploratory leaching test of Nochar and Nochar-immobilised oils implemented in 2022-2023 is briefly described in Appendix C(II). The properties and behaviour of these materials are less mature, and the acceptance of this type of waste form is not currently accepted.

Currently, no protocol is available for the long-term durability of a new matrix. Some of the main general ANDRA requirements related to the immobilisation of ROLs can be cited:

- Absence of products/mixtures presenting risks of inflammation, and/or exothermic reactions detrimental to the integrity of the final package
- Absence of free liquids (aqueous and organic)
- Absence of absorbent substances as a component of the package manufacturing process
- Waste swelling by water uptake: Assessment of swelling and its effects on the mechanical strength of the waste block
- Non-dispersible solid blocks that do not contain water and are likely to be released under disposal conditions.

ITALY

The requirements, referred to as cement conditioning, are based on the Italian Technical Guide (TG) n. 33 [23], UNI standards [24], [25], [26] and the preliminary WACs for waste acceptance at the National Repository [27], developed by SOGIN. TG n. 33, and UNI standards include the majority of preliminary WACs.

TG n. 33 is issued by the National Inspectorate for Nuclear Safety and Radiation Protection (ISIN) and establishes safety and radiation protection criteria that must be respected for the safe management of RW. It provides criteria and requirements for VLLW, LLW, ILW treatment, and cement conditioning (homogeneous and heterogeneous waste form, containers, and package qualification) to demonstrate long-term durability.

UNI standards [24], [25], [26] provide criteria, requirements, and procedures for LLW and ILW cement conditioning (homogeneous and heterogeneous waste form, containers, and package qualification). In particular:

- UNI 11784-2020 is the reference for ILW heterogeneous
- UNI 11930-2023 is the reference for ILW homogeneous

- UNI 1613904 is the reference for heterogeneous and homogeneous LLW (expected to be published in 2025).

The preliminary WACs provide indications on how waste must be managed, treated, and conditioned for potential acceptance into the future National Repository. They refer to waste, waste form, and package, and also include indications of the methods of conditioning RW based on their specific characteristics. The requirements for waste form vary according to the radiological classification and characteristics of the waste (e.g., specific requirements exist for homogeneous or heterogeneous waste forms [23]).

LLW

Homogeneous LLW

Matrices/waste form:

- Compressive Strength (CS) ≥10 N/mm² after 28 days of curing [28], [29], [30], [31]
- Resistance to Thermal Cycles: No cracks or surface damage and CS ≥10 N/mm² after 30 cycles of 24 hours from –40°C to +40°C [26]
- Radiation Resistance: No cracks or surface damage and CS ≥10 N/mm² after an integrated dose of 10^6 Gy [26]
- Biodegradation Resistance: No cracks or surface damage, and CS ≥10 N/mm² after incubation with fungi [32]
- Fire Resistance: Non-combustible or self-extinguishing [33]
- Leaching Resistance: High resistance to leaching, L(Cs) ≥6 [34]
- Immersion Resistance: No swelling or surface damage, and CS ≥10 N/mm² after 90 days of immersion [26].

Waste package (conditioned waste and container):

- Free liquids: <1% of the useful internal volume of the package [2]
- Gas generation: The generation of gas within the package due to interactions between the conditioning matrix and waste must be evaluated [26]
- Presence of voids: Void percentage <10% of the package volume
- Requirements for transport: The tests must be integrated with the requirements of the International Atomic Energy Agency (IAEA) SSR-6 [35]

Container:

- Resistance to degradation (reference period of at least 50 years (for VLLW/LLW) and 100 years for ILW) to be demonstrated by degradation tests (e.g., corrosion) under harsh environmental conditions [25]
- Tightness [36]

Heterogeneous LLW: Same as homogeneous waste, with two additional requirements:

- Water Permeability: Average penetration ≤20 mm; maximum penetration ≤50 mm [37]
- Waste Coverage: The thickness of the waste coverage by the encapsulating matrix must be at least 2.5–3 cm (to be assessed based on radiological content).

ILW: Same requirements as heterogeneous LLW, with modifications and/or additional requisites:

Homogeneous ILW:

- Radiation Resistance: No cracks or surface damage and CS ≥10 N/mm² after an integrated dose equivalent to the total dose generated in the waste form over approximately 300 years (10^7 Gy) [25]
- Leaching Resistance: L(Cs) ≥7 [34]
- Gas Permeability: Qualitative; the obtained permeability value is compared with internationally established parameters for waste encapsulation matrices [38]
- Dimensional Stability: Axial shrinkage <2000 µm/m [39]

Heterogeneous ILW: Same as homogeneous ILW with the following modifications:

- Leaching Resistance: L(Cs) ≥6 [34]
- Waste Coverage: The minimum thickness of waste coverage by the encapsulating matrix must be greater than 5 cm.

NETHERLANDS

At this moment, no explicit national requirements on the stability of waste forms exist regarding the chemical, physical, and mechanical properties, as no host rock, site, and disposal concepts have been chosen yet. For long-term interim storage, WAC for several groups of "standard wastes" are defined in [40], which mainly places restrictions on the contact dose rate, activity, weight, and moisture content. For other waste, specific requirements are defined in cooperation with the client/waste producers. The current (conditional) safety cases conservatively consider instant mobilisation of radionuclides after closure of the repository for LILW, and instant mobilisation of radionuclides at 1000 years after closure of the repository for HLW.

POLAND

In Poland, there are no national requirements for the stability of waste forms regarding their chemical, physical, and mechanical properties. Waste matters are regulated by the Waste Act [41] and Directive 1999/31/EC of the Council of the European Union on waste management [42].

ROMANIA

Romanian legislation on RWM [43], [44] includes safety requirements for the predisposal and disposal of radioactive waste, without specific requirements and criteria for waste form stability. Based on WAC for disposal, waste processors have developed internal standards approved by the National Commission for Nuclear Activities Control (CNCAN, Romanian regulatory body) that specify all the tests that have to be performed to prove the disposability of the waste packages they are producing. These internal standards include requirements for waste packages and the means of verifying their performance, as well as the requirements for the waste forms (mainly leachability and mechanical strength).

The requirements and criteria for waste forms and packages are also included in WAC for disposal. The WAC for National Repository Baita Bihor (DNDR), besides radiological criteria (activity concentration and total activity for different short-lived and long-lived radionuclides, and dose rate) specifications for waste forms and waste packages:

- Radioactive waste must be solidified/immobilised in stable waste forms; cement-based matrices (CEM II) and bitumen are currently used and accepted at DNDR.
- Radioactive waste must be packaged to ensure stability during the disposal period, with a low leaching rate for the radionuclides contained (standard 200 L drums and 400 L drums are accepted for disposal).
- Under normal temperature and pressure conditions, the RW must not react with each other or with the conditioning matrix, decompose by explosion, detonate, or react explosively with water.
- The solid or solidified radioactive waste has to contain as little as possible free liquid (maximum 1% of its volume), and this free liquid has to be noncorrosive.
- the auto-ignition temperature shall not be less than 300°C.
- minimum mechanical strength (5 MPa, after 28 days of curing).

According to the preliminary WAC for future near-surface disposal facilities (DFDSMA), it is accepted for the disposal of solidified homogeneous waste and immobilised heterogeneous waste. A cement matrix is convenient in both cases, and other matrices are possible.

- The waste form must be solid, compact, not easily dispersible, and chemically stable.
- Free spaces inside the radioactive waste package should be reduced as much as possible.

- The disposal container should isolate the solidified waste for 300 years. This means that after a 300-year underwater immersion, the container is still hermetic, and the leaching characteristics are guaranteed.
- The minimum thickness of the disposal container: an empty container with this thickness withstands at least a load of 250 kPa.
- No sweating/swelling from the solidified block will occur during 300 years.
- No residual water shall remain after 24 h curing.
- A maximum of 10 % (volume) of voids is allowed, provided that the compressive strength criterion is met, on a representative sample, with the same proportion of voids.
- Minimum mechanical strength for homogeneous solidified waste (5 MPa after 28 days of curing).
- Minimum mechanical strength for the conditioning matrices used for homogeneous solidified waste (20 MPa for mineral matrices and 8 MPa for organic matrices).

SPAIN

Spanish WAC, for VLLW and LILW, include radiation safety-related criteria (dose rate, surface contamination, alpha-beta/gamma specific activity), general mechanical requirements for waste forms (compression resistance), waste packages (voidage, drop test), and certain physico-chemical requirements, such as leaching rates for specific radionuclides.

Chelating and complexing agents must be identified and, in some specific cases, limited. A limit on the organic liquid inside the cemented waste blocks of liquid homogenous waste has also been set in the national WAC. Non-radiological hazardous contaminants (e.g., Asbestos, Cl, F- polymers) are currently not accepted for disposal.

Free liquids, as well as organic and reactive wastes that have the potential to generate gas, are forbidden. For safety reasons, wastes that present the risk of explosion, ignition or internal pressure build-up are banned from disposal.

UKRAINE

The radioactive waste management system used today in Ukraine is based on the requirements of the documents [45]. A detailed table presenting the WAC for LLW and ILW disposal routes in Ukraine from the perspectives of radiological criteria, chemical properties, physical properties, mechanical properties, and biological properties is listed below in Table 4.

Table 4: Acceptance criteria for Intermediate Level and Low-Level Waste disposal route in Ukraine.

	LLW disposal route	**ILW disposal route**
Radiological criteria		
Radionuclide content and specific activity	Both conditions must be met: - Total package specific activity: Total alpha activity < $3.7.10^{6}$ Bq.kg^{-1}; - Individual RN specific activity < limit: see tables: Table 1 and Table 2.	RN content must have fully characterised. The RN content is limited to activities compliant with operational safety regulations. This compliance must be demonstrated for the packaging type used, RN content for accidental scenarios (transport & lifting accidents) RN content must be compliant with intermediate storage WAC.
Surface dose rate and dose rate at reference distances	2 mSv/hr on surface	n/a (remotely operated handling)
Surface contamination	40 Bq/100 cm^2 for alpha emitters and 400 Bq/100 cm^2 for beta/gamma emitters	40 Bq/100 cm^2 for alpha emitters and 400 Bq/100 cm^2 for beta/gamma emitters

Spatial distribution of RN	As homogenous as possible Less than 80% of package activity in any 0.2m^3 volume	n/a
Criticality		The package's absence of criticality (including the case of the neighbouring package contributing to criticality) must be demonstrated.
Chemical properties		
Chemical compatibility - Chemical stability	Requires other chemical properties to meet acceptance criteria	
Leachability	LIX>6 or for the diffusion coefficient of solidified radioactive waste form is 10-6 cm^2/s	
Active substances	Reactive metals Al: <0.1m^2 for each 330 L of internal package volume, 0.1m^2 for 220 L drums. Surface multiplied by 10 if Al is wrapped in a plastic bag. Mg, Zn and other reactive metals must be conditioned in packages injected with a hydrophobic matrix (polymer)	
Corrosivity	Corrosive material < 1% of total package mass	
Corrosion resistance	Waste package durability must exceed 300 years	
Chelating and complexing agents	Chelating and complexing agents < 1% of total package mass	Waste containing chelating or complexing agents material must be conditioned separately; Chelating agents and complexing content must be characterised. Specific treatment (to limit RN mobility) is required to limit the mobility of RN in waste packages containing chelating or complexing agents.
Free liquid content	No free liquid	No free liquid
Flammability	The package can withstand an 800°C fire for 30 minutes or more if it is an organic matrix.	The package withstands 800°C fire for 30 min or more.
Ignitability	See also active substances. No other pyrophoric low flammable or flammable materials in packages	No other pyrophoric low flammable or flammable materials in packages, unless treated for passivation
Explosivity	No explosive material	No explosive material
Gas generation and content	No gas container – No pressurized container Gas generation limited to a quantity not compromise storage safety. No waste producing flammable gas when in contact with water	No gas container – No pressurized container Gas generation limited to a quantity not compromise storage safety. No waste producing flammable gas when in contact with water
Toxic constituents	As per applicable regulations for comparable non-radioactive waste disposal	
Biological properties		
Organic content	Organic content should be immobilised in a cement matrix.	Waste containing organic material must be conditioned separately; Organic content must be characterised. Specific treatment (to limit RN mobility) is required to limit the mobility of RN in waste packages containing organic material.
Mechanical properties		

Structural stability Strength	compressive strength for concrete matrix in disposal containers >5 MPa and immobilisation material thickness > 5 cm	compressive strength for concrete matrix in disposal containers >8 MPa and immobilisation material thickness > 5 cm
Permeability and porosity	Minimum allowing gas ventilation	Minimum allowing gas ventilation
Homogeneity	As reasonably achievable	n/a
Cavities – homogeneity	For metallic waste, top void volume must be kept < 3% of container volume	cavities kept to a minimum by reasonably achievable methods
Heat emission	n/a	Thermal power must be characterised. Very low thermal power (>2kW/m3) is suggested
Thermal resistance	See flammability	
Identification and packaging		
Package identification method	Individual ID, recorded in a waste tracking system with waste package characteristics	Individual ID, recorded in a waste tracking system with waste package characteristics
Physical properties		
Density	Maximum reasonably achievable. Package weight must be kept under maximum container limit and handling and lifting capability, when known	

4. Key parameters of waste forms and representative conditions of disposal facilities to be investigated in L'OPERA

The long-term management of LILW requires careful consideration of the key parameters of waste forms and representative conditions of disposal facilities. Waste forms must be designed to ensure the stability and containment of radioactive materials over extended periods. This includes selecting materials resistant to degradation, such as corrosion and leaching, thereby minimising the potential release of radionuclides. Additionally, the waste forms should be compatible with the environmental conditions of the disposal facility, such as the temperature, humidity, and geological stability. Representative conditions of disposal facilities include robust containment systems, effective isolation of waste from degradation, and continuous monitoring to detect any potential breaches. Facilities must also be designed to withstand natural events, such as earthquakes, floods, and temperature variations. However, our primary focus is on the study scope of WP7: to dispose of LILW at (near-)surface or intermediate-depth disposal facilities and ensure the durability and safety of new matrices for an expected period of 300 years.

Long-term durability encompasses the effective resilience of waste materials within their matrices, and the interaction between waste forms and the environment. Specifically, in terms of chemical durability, waste forms must maintain chemical stability over the anticipated duration, ensuring that they contain radionuclides and prevent their leaching or release. Additionally, waste forms must withstand chemical reactions, whether occurring between the waste and the matrix or between the waste forms and the environment, which could potentially lead to the release of radioactivity. Regarding physical durability, waste forms must be robust against alterations that could change their structure and must endure expected environmental conditions such as temperature fluctuations, radiation, humidity, and other factors over time. For mechanical durability, waste forms need to retain their mechanical strength and withstand mechanical stress under anticipated load conditions during handling and long-term disposal. A summary is presented in Table 5.

Table 5: General criteria related to long-term durability at the interaction between wastes and matrices, and the interaction between waste forms and the environment.

Interaction:	wastes and matrices	waste forms and the environment
Chemical durability	• Contain radionuclides; • Maintain stability and resist chemical reactions between the waste and the matrix.	• Resist chemical reactions between waste forms and the environment.
Physical durability	• Resistance to alterations regarding the structure of waste forms.	• Resistance to alterations in structure and expected environmental conditions.
Mechanical durability	• Retain mechanical properties; • Resist mechanical stress.	• Resist mechanical stress under load conditions in long-term disposal.

This section is organised into two main parts. The first part investigates the factors influencing the durability and stability of matrices and waste forms from a material perspective, considering the interests of partners to be explored in L'OPERA. The second part examines the environmental conditions within disposal facilities over extended periods, with a particular focus on the conditions relevant for defining leaching and ageing tests to be implemented in T5 within L'OPERA.

4.1 Key parameters influencing the long-term behaviour of waste forms to be investigated in L'OPERA

This subsection provides a summary of the waste form properties that partners are keen to investigate within the L'OPERA project, with a particular emphasis on long-term management. L'OPERA aims to explore and evaluate various innovative waste forms to ensure their effectiveness and stability over extended periods, which is crucial for the safe containment of radioactive materials. Partners are interested in examining a range of waste forms, each tailored to immobilise specific types of radioactive waste. The focus on long-term management involves assessing the chemical, physical, and mechanical durability of these waste forms. By investigating these properties, L'OPERA aims to improve the knowledge of the durability of waste forms that can safely and effectively contain radioactive materials.

BELGIUM

SCK CEN will investigate the stabilisation of incineration ashes and lead wastes using ion-rich glass-blended cement and ion-rich glass-based geopolymers as conditioning matrices. The chemical resistance of the waste forms will be evaluated through leaching tests under alkaline, water, and accelerated conditions using NH_4NO_3 (with and without radionuclides), accelerated carbonation under 1% CO_2, stability assessments in water, alkali-silica reaction (ASR) analysis, heat release measurements via isothermal calorimetry, and fire resistance tests in collaboration with the University of Pisa. The key properties will be assessed after durability testing, including transport properties (diffusion and permeability), alteration in minerology, and microstructure (characterised using SEM, TGA, NMR, FTIR, N_2-adsorption, and MIP). Furthermore, their mechanical properties will be studied.

CZECH REPUBLIC

The Czech team (UJV Řež, CVŘ, FJFI ČVUT, and SÚRAO) will investigate IERs immobilised in Metakaolin-based geopolymer matrix. The IERs will be doped with stable elements, and for selected leaching experiments, radionuclide-doped IERs will be used. Long-term leaching tests will be conducted using water from the Dukovany repository (see Table 7), focusing on parameters such as:

- Chemical composition of the leachate
- Radionuclide release
- Changes in microstructure
- Changes in compressive strength

To accelerate leaching processes, column leaching experiments will be performed on crushed, non-radioactive samples. Additionally, the effects of irradiation and thermal cycling on the geopolymer matrix will be studied.

FINLAND

Finnish waste management organisations rigorously test waste forms to ensure durability and radionuclide containment. To obtain approval for the disposal of new forms of waste, it is essential to demonstrate their long-term safety. In WP7, to utilise ordinary Portland cement (OPC) and geopolymer for IER, the following properties of waste forms need to be tested:

Chemical properties:

- Leaching behaviour
- Radionuclide solubility & release under repository conditions
- Stability of waste forms immersed in water for 7 days (no breaking allowed)
- Microstructural changes (mineralogical phases)
- pH of waste forms (must be alkaline)

Physical properties:

- Porosity
- Diffusion rates/coefficients
- Homogenization
- No air bubbles are allowed inside the waste forms, and they cannot be in a water-soluble phase.

Mechanical properties:

- Compressive strength (after 28 days)
- Long-term stress simulations and load-bearing assessments are conducted to ensure that they meet Finnish disposal safety requirements.

FRANCE

In L'OPERA, ORANO, and CNRS-PIMM (French National Scientific Research Centre located in the Process and Engineering in Mechanics and Materials Laboratory), ANDRA is studying the durability of oil encapsulated with Nochar. This type of waste is not currently accepted for disposal. The free liquid and oil release are not accepted for disposal based on their biohazards and environmental impact.

The understanding of the durability over the long term is not available. The release of organic molecules and oil will be followed during and after ageing procedures (irradiation and leaching under basic conditions), and the lifetime durability will be estimated. The difficulty in establishing lifetime durability is defining a criterion for oil release and an associated value. Currently, this release value (considered by ANDRA) is zero for all disposal periods.

The oil retention properties inside Nochar N910 (chemical characterisations, density, porosity, and microporosity) are important parameters to study.

- In the initial state, during ageing N910 and oils immobilised by N910 (thermal and irradiation), and after leaching,
- The overall evolution of macroscopic and microscopic properties after ageing/leaching.

ITALY

The main properties of waste forms to be considered for the evaluation of long-term behaviour (derived mainly from preliminary WACs) are as follows:

- Chemical properties such as leaching/leakage rate, concentration of complexing and chelating agents, volume fraction of absorbent material to liquid wastes or soluble material, content of chemical toxic and infective materials, content of reactive or corrosive materials, gas production, heat production, content of organics, oils, fats, paraffins, flammable/explosive/oxidizing properties, etc.
- Physical properties: solid waste form is currently considered for preliminary WAC (e.g., free liquids in the waste package must be lower than 1%), porosity, density, homogeneity, voids, etc.
- Mechanical properties, such as compressive strength and resistance to mechanical impact (drop test).

POLAND

In L'OPERA, Polish partners are exploring the use of geopolymers to immobilise complexing agents (such as oxalates, EDTA, etc.) and organic liquid wastes (such as IERs). The properties of interest to investigate include the following.

- Chemical properties: leaching rate, concentration of complexing and chelating agents, chemical kinetics, relationship of the mass of absorbent material to liquid wastes, content of chemical toxic and corrosive materials, gas and heat production, heat production, organics, off-gas production, flammability/explosivity, and fire resistance.
- Physical properties: homogeneity, package properties (size/volume/material), temperature, and package pressure.
- Mechanical properties: compression resistance, drop resistance, and mechanical strength.

ROMANIA

While Romanian requirements align with international recommendations, additional investigations could focus on enhancing the understanding of the new conditioning matrices (geopolymer, MKPC) and waste form behaviour under long-term disposal conditions to qualify them and to demonstrate that these new matrices can accomplish the WAC for final disposal.

Regarding the waste form obtained by radioactive incineration ash immobilisation in geopolymer matrix (metakaolin-based), the key properties of interest to be investigated in L'OPERA include the following:

- Effect of ageing (radiation) on waste form mechanical properties (compression and flexural strength) and structure (by optical microscopy and SEM/EDS TGA/DTA)
- Long-term leaching behaviour

SPAIN

Achieving a better understanding of the medium to long-term effects of organics inside matrices is a key point for Spanish end-users and stakeholders. The definition of standardised tests or protocols for their measurement/monitoring is a topic of special interest. Similarly, the elucidation of which organic compounds are the most problematic for the stability of the waste forms and the role they play in the degradation mechanisms of the matrices will also be considered for the long-term performance of the waste forms.

The long-term stabilisation of not only radionuclides but also toxic and hazardous chemical elements is of significant relevance in our national context. Therefore, in the framework of L'OPERA, leaching of both inorganic elements and organics resulting from the degradation of different types of waste forms will be assessed. Special attention will be paid to the speciation of the released organic by-products. Other issues to be considered in this work package are the study of waste/matrix compatibility and the interactions between waste forms and Near Field in conditions representative of the expected long-term evolution of the EBS.

Regarding the physical properties of geopolymer and MKPC waste forms, the evolution of porosity, internal gas pressure build-up, and microcracking are parameters/processes of interest to be studied to assess the compatibility of different waste and conditioning matrices. Another key issue considered in the experimental program developed for this work package is the evolution of mechanical performance over time of the waste form/matrix, including dimensional stability, potential swelling issues or compression resistance.

UKRAINE

The system to be investigated in L'OPERA uses a geopolymer for the immobilisation of oils. The acceptance criteria for ILLW disposal routes in Ukraine are explicitly stated in Section 3.2. The properties to be investigated in L'OPERA are briefly summarised as follows:

- Chemical properties: leachability, active substances, corrosivity, corrosion resistance, chelating and complexing agents, free liquid content, flammability, ignitability, explosivity, gas generation and content, toxic constituents, heat emission, and thermal resistance
- Physical properties: permeability and porosity, homogeneity, radiological content and specific activity, individual RN-specific activity, surface dose rate and dose rate at reference distances, surface contamination, and spatial distribution of RN
- Mechanical properties: compressive strength of the concrete matrix in disposal containers, immobilisation material thickness, and strength.

In summary, partners have identified the material properties of waste forms and matrices of interest to be investigated in WP7. These properties include parameters related to waste form production, such as waste solidification, absence of air bubbles/water-soluble phases, and the volume fraction of absorbent materials to liquid wastes. Additionally, they have listed properties of waste packages, including package size, volume, materials, pressure, and drop test resistance.

However, since L'OPERA focuses on the key parameters that influence the long-term durability of matrices and waste forms, the study will exclude aspects related to waste form production and waste packages. In summary, excluding the properties related to waste form production and waste packages, the key parameters influencing the long-term durability of matrices and waste forms to be evaluated in WP7 include the following:

- Chemical properties: leaching rates, chemical kinetics, pH, biodegradation, content of free liquid, ASR, active substances/reactive metals, gas production, corrosion, concentration of complexing and chelating agents, content of organics, radionuclide solubility and release, radiolysis of organic compounds, content of chemically toxic and corrosive materials, changes in macromolecular structure, and chemical structure and characteristics of the released organic by-products
- Physical properties: porosity and microporosity, specific surface, density, homogeneity, temperature, shrinkage, dustiness, internal gas pressure, microcrack generation, gas permeability, diffusion rates, dimension variation/swelling, surface dose rate, dose rate at reference distances, radionuclide content, and specific activity.
- Mechanical properties: compressive strength, flexural strength, toughness, and creep.

4.2 Representative conditions of disposal facilities

This section focuses on defining the representative conditions prevailing in disposal facilities and provides a detailed analysis divided into two interconnected parts. The first part is dedicated to the leaching test, which is designed to evaluate the potential for radionuclide release from waste forms when exposed to various environmental conditions. When immobilising oil with Nochar, a key evaluation factor is the release of oil from the waste forms. This test is essential for understanding how waste forms interact with water and other fluids over time, ensuring that containment systems remain effective and prevent the migration of radioactive materials into the environment.

The second part addresses the ageing test, which examines the long-term durability and stability of waste forms under conditions that simulate the expected environmental conditions over extended periods. These include factors such as temperature fluctuations, radiation exposure, humidity, and chemical interactions. By defining such factors in T3, the ageing tests in T5 can assess how these conditions impact the performance of waste forms and provide critical insights into their long-term behaviour and reliability.

Together, these tests form a comprehensive framework for evaluating the safety and effectiveness of disposal facilities in managing LILW in the long term. By linking these tests to the broader context of T5, this section provides a thorough understanding of how disposal facilities can maintain their safety and integrity, thereby enhancing the overall effectiveness of long-term radioactive waste management strategies.

4.2.1. Key (geo)chemical parameters in the disposal concept related to leaching tests

Defining key geochemical parameters for leaching tests is essential to accurately assess the potential release of radionuclides from waste forms under various environmental conditions. These parameters include the pH level, which influences the solubility and mobility of radionuclides, and the redox potential, which affects the oxidation state, stability of radioactive elements, and chemical stability of matrix/waste forms. Additionally, the concentration of major ions, such as calcium, magnesium, sodium, and potassium, in the leachate can affect the dissolution and precipitation processes of waste form components. The presence of complexing agents such as organic acids or chloride ions can also alter the speciation and mobility of radionuclides. Temperature is another critical parameter, as it can accelerate chemical reactions and influence the solubility of waste form constituents. By carefully monitoring and controlling these geochemical parameters, leaching tests can provide valuable insights into the long-term behaviour and stability of waste forms.

BELGIUM

For Belgium, representative cementitious pore solution is of interest. The leaching protocol developed in the PREDIS project will be adopted, which defines short-term and long-term stability testing under synthetic cementitious water, including minimum requirements for solution analysis and solid characterisation. Additional details of the defined reference protocol are provided in Appendix D.

CZECH REPUBLIC

As explained in Section 4.1, the Czech Republic is interested in the long-term performance of the implemented geopolymer matrix in the repository environment. Two main types of water are considered, representing the disposal conditions of the Dukovany repository:

- water collected by the drainage system (Table 6), which is collected in a reservoir, and its composition slightly changes during the year;
- rainwater in the vaults (Table 7).

Table 6: Water composition in the drainage system of the Dukovany repository; sampled 25.10.2022.

Cl^-	NO_3^-	SO_4^{2-}	SiO_3^{2-}	HCO_3^-	Na	K	Mg
(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
83.6	10.10	33.1	15.1	304	35.0	22.2	20.8
Ca	Fe	Al	Sr	TOC	pH	κ	ORP
(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(-)	(µS/cm)	(mV)
87.1	0.030	87.1	0.330	2.81	8.15	810	150

Table 7: Water composition in the vault of the Dukovany repository; sampled 04.04.2025.

Cl^-	NO_3^-	SO_4^{2-}	SiO_3^{2-}	F^-	Na	K	Mg
(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
<1.00	11.6	7.40	7.61	<1.00	16.7	32.1	1.21
Ca	Fe	Al	Sr	$KNK_{8.3}$	$KNK_{4.5}$	pH	K
(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mmol/l)	(mmol/l)	(-)	(µS/cm)
15.5	n.d.	n.d.	<1.00	0.057	2.02	8.35	237.5

FINLAND

As part of the WP7 L'OPERA, leaching tests are conducted to evaluate the long-term stability of OPC and geopolymer waste forms under Finnish repository conditions. The key geochemical parameters to be assessed include the following:

- Solution composition: The leaching environment replicates Finnish groundwater, incorporating Na-Ca-Cl-dominated solutions to evaluate material degradation over time.
- pH stability: The influence of alkaline plume interactions from OPC waste forms should be studied, along with the long-term pH stability of geopolymers.
- Salinity variations: The effect of saline groundwater on the geopolymer phase stability and OPC leaching behaviour should be analysed.

FRANCE

After the saturation of disposal, the waste will be in contact with the cementitious water. ANDRA has established a technique to test and evaluate the leaching resistance of homogeneous waste forms. Additionally, for CSA, ANDRA defined a cementitious water composition for leaching experiments. The cementitious solution is composed of demineralised water filtered after lime saturation, with an initial pH of the solution of 12,5, and it will be used for leaching experiments in L'OPERA for testing Nochar/oil waste forms.

ITALY

In Italy, since the National Repository siting process is ongoing, no specific key geochemical parameters have been defined. However, Italian TG n. 33 evaluated the leaching behaviour of solidified radioactive waste using the ANSI/ANS-16.1-2019 procedure [34]. The leaching index must be L(Cs)≥6 for all waste types, except for homogeneous ILW, where the value must be L(Cs)≥7.

NETHERLANDS

Dutch partners are not involved in the experimental study in WP7. However, their geological disposal conditions are outlined below and have contributed to establishing the boundary conditions for L'OPERA.

During disposal in rock salt, no leaching will occur in the normal evolution scenario. In some unlikely altered evolution scenarios, water may intrude owing to failures during the closure of the facilities or undetected brine inclusions. In the very long term (over tens of millions of years), suberosion of salt formation may also lead to the intrusion of water. The intrusion of water quickly transforms into a highly saturated brine. Depending on the altered scenario and the source of the intruding solution, different types of brine may come into contact with the waste container. Pure brine systems are usually described by the quinary system Na^+, K^+, SO_4^{2-}, Mg^{2+}/Cl^- / H_2O [46], [47], and may develop into Q- or R-brine. Brine pockets often exhibit Mg-dominated compositions [48]. When brines are in contact with cementitious barriers, the development of Q-brines is likely. Because brines can quickly corrode iron-based waste canisters, additional colloidal particles with high sorption properties may be produced, potentially increasing radionuclide mobility via facilitated transport processes.

In clay disposal, intruding pore water from the host rock water first comes into contact with cementitious material from the gallery lining and backfill material from the EBS, which results in an alkaline solution with pH values of up to 13, slowly decreasing in time after dissolution of the oxide phase. In addition to pH evolution, mineral equilibria also alter the redox potential. While alkaline solutions, in principle, have lower corrosion rates, iron-based waste canisters fail in the long term, and corrosion products may be present as colloidal particles with high sorption properties that may enhance the mobility of radionuclides.

POLAND

The interested (geo)chemical parameters to be considered for the leaching tests in L'OPERA are:

- Chemical composition of the environmental aqueous streams,
- Acidity,
- Red/ox properties.

ROMANIA

In the National Repository Baita Bihor, waste packages (200 L/400 L) are disposed of in galleries and bentonite is used as the filling material. *Due to the high amount of cement in the disposal galleries, the porewater pH is alkaline (10-11) for a long period of time, and oxidic conditions are prevalent.*

In the current design, the EBS of the future near-surface disposal facility to be constructed for RW generated by the Cernavoda NPP is mainly based on cementitious barriers. The conditioned RW (standard drums 200/400 L) is placed in reinforced concrete cubic containers, and the empty space is backfilled with mortar to form monoliths. These monoliths (disposal modules) are placed in a disposal cell (made of reinforced concrete), and sand is used as filling material. After filling, the disposal cells are sealed with a concrete slab, and when all disposal cells are filled and sealed, a multilayer cover composed of natural (sand, gravel, loess, clay) and artificial materials (waterproofing membranes) will be constructed to restore the natural landscape. *As the waste form is predominantly cement, the porewater pH is highly alkaline (12-13) for a long period of time, and oxidic conditions are prevalent.*

SPAIN

According to the reference scenario used for the Safety Assessment of the disposal facility, the geosphere is conservatively assumed to be saturated, as well as the EBS system. During the institutional control phase (i.e., <300 years) it is presupposed that the porewater from concrete barriers (overpacks and bottom slab) is in chemical equilibrium. No credit is given to the disposal cell slab, control network or unsaturated zone.

After the end of this period (>300 years), it is accepted that:

- All engineered barriers, including disposal containers and waste matrices, are completely degraded
- Water infiltration rate is similar to the natural percolation values in the site
- Leaching is controlled by chemical equilibrium between cement porewater and groundwater
- Leached activity immediately reaches the saturated zone.

In both cases, water interacting with the waste forms will consist basically of CEM I porewater, as CEM I 42,5 R/SR is the reference binder used in El Cabril for backfills and the manufacturing of the disposal units.

Chemical composition of cementitious leachates sampled from disposal vaults corresponds to a K-Na-SO_4 water with average parameters: pH 12,3; CE: 11,2 mS/cm; alkalinity: 61,2 meq/l.

For the design of the leaching tests, three scenarios have been considered, and for each of them, a different type of leachant has been selected:

- Normal operation (institutional control period < 300 y): CEM I-type pore water (pH 12.4), considering available data from the surveillance program.
- Groundwater infiltration (e.g., failure of impermeabilisation/high water table scenario): water sampled on-site in disposal platforms.
- Meteoric water intrusion/flooding: ultrapure water[1]

The selection of ultrapure water and sampling points in the facility has been done based on the historical records available from the Surveillance Program (rainfall chemical composition and platform drainage system, respectively).

UKRAINE

The main (geo)chemical parameters that must be considered for defining the leaching tests in T5 include:

- pH: effect of acidic or alkaline conditions,
- Redox conditions: oxidation-reduction reactions,

In summary, cementitious pore solution has been identified as the most representative disposal condition for leaching experiments. This is due to the fact that cementitious materials are used in disposal vaults, and conditioned RW is placed in concrete containers with mortar internally grouted in some countries. Alternatively, an alkaline solution with a high pH has been considered. These common conditions establish a framework for assessing the stability and leaching behaviour of various waste forms in a cementitious pore solution. Additionally, partners have taken into account specific national representative disposal conditions, such as water collected by the drainage systems, rainwater in vaults, groundwater from the repository site, ultrapure water, and acidic solutions. The key geochemical parameters related to leaching tests include solution composition, pH, and redox conditions.

[1] ultrapure water also used for QC leaching tests

4.2.2. Long-term environmental conditions related to ageing tests

This subsection focuses on defining the environmental conditions to be considered for the ageing tests in T5. Characterising long-term environmental conditions for ageing tests is crucial for understanding the durability and stability of waste forms. These tests simulate the environmental stresses that waste forms encounter in disposal facilities, such as temperature fluctuations, radiation exposure, humidity, and chemical interactions. Temperature variations can accelerate the kinetics of chemical reactions and affect the physical integrity of waste forms, whereas radiation exposure can induce structural changes and degradation. Humidity levels influence the moisture content within the waste forms, which can result in corrosion or leaching of radionuclides and impact the transport behaviour of waste forms related to carbonation, for example. Additionally, the presence of various chemical agents in the environment, such as acids, bases, and salts, can interact with waste forms, impacting their long-term stability. By accurately replicating these conditions in ageing tests, researchers can assess how waste forms will perform over time.

BELGIUM

For the long-term ageing, the carbonation resistance test is planned, which is relevant for surface disposal (and also for geological disposal in Belgium, as high CO_2 in Boom Clay). A standard protocol to follow is outlined in EN 12390-12:2020 (1% CO_2, 20°C, 60% relative humidity (RH)) [49].

CZECH REPUBLIC

In addition to the irradiation tests with a cumulative dose for 300 years of 1 MGy, the expected climatic environmental conditions are: a temperature in vaults of approximately 8-10 °C and average annual total atmospheric precipitation of 487 mm, as shown in Table 8.

Table 8: Expected long-term condition

Expected water composition	Table 6 and Table 7
Expected cumulative dose (300 y)	1 MGy
Temperature in vaults	8-10 °C
Average annual total atmospheric precipitation	487 mm

FINLAND

In WP7, VTT does not perform any ageing tests. However, the key environmental conditions that should be considered when assessing the stability of OPC and geopolymer waste forms include the following:

- Temperature fluctuations: ambient temperature of the repository and its effect on thermal expansion, microcracking, and phase instability.
- Climatic variations: both short- and long-term impacts, including the potential impact of glacial cycles and permafrost penetration, which could reach repository depths after 30,000 years (RCP4.5, RCP2.6).
- Irradiation resistance: the long-term effects of gamma radiation on waste form integrity.
- Flow of groundwater: Finnish disposal sites are chosen for low hydraulic conductivity and reducing mineral-rich groundwater to limit corrosion and radionuclide mobility.

- Groundwater chemistry evolution: The transition from oxidising to reducing conditions and its effect on material degradation.
- Increased precipitation: particularly relevant for near-surface repositories.
- Carbonation effects: the long-term CO_2 uptake in OPC and geopolymers should be assessed, as this can alter the microstructure and impact radionuclide retention properties.

FRANCE

The total irradiation dose in the surface disposal of waste packages differs according to the type of waste. For surface disposal, the total dose of waste packages can reach approximately 1 MGy. ANDRA established a technique test for cementitious materials to evaluate their resistance to irradiation. Gas production by radiolysis, dimensional modification, and mechanical behaviour after irradiation are evaluated in this test. This test is not applicable to all materials. Based on general information about the maximum integrated dose, an ageing protocol will be defined to accelerate the ageing of Nochar/oil systems to understand degradation and its effect on oil release.

ITALY

Italian TG n. 33 defines ageing tests to evaluate the long-term durability as

- Resistance to Thermal Cycles: No cracks or surface damage and CS ≥10 N/mm² after 30 cycles of 24 hours from –40°C to +40°C, RH 90±5%, and a thermal gradient ≥10K/h [25], [26].
- Thermal ageing: not currently included in TG n. 33, but evaluated case-by-case based on the decay heat expected for ILW.
- Radiation Resistance: No cracks or surface damage and CS ≥10 N/mm² after an integrated dose of 10^6 Gy (10^7 Gy for ILW[2]) [25], [26].
- Biodegradation Resistance[3]: No cracks or surface damage and CS ≥10 N/mm² after incubation with fungi [32].

NETHERLANDS

The impact of long-term radiation on the waste matrix, induced radiolysis, and the effect of the radiolysis products on the waste matrix behaviour are of interest.

POLAND

The important long-term environmental conditions to be considered are:

- Temperatures (low/high),
- Humidity,
- Total radiation dose.

[2] The test can be conducted up to 10^6 Gy if the integrated gamma dose over a period of 300 years will not exceed that value.
[3] This test can be omitted if the organic material is less than 5%

ROMANIA

The internal standards mainly cover the criteria and requirements for the durability of waste packages (waste form and disposal container), and not for the waste form. These are specific to short-lived low- and intermediate-level institutional waste, as only this class of radioactive waste is currently processed for final disposal. The chemical stability, physical integrity, and mechanical properties of the waste packages must ensure the containment of radioactivity for at least 300 years.

Processes that can affect waste form mechanical strength, permeability, and porosity, as well as the release of radionuclides and hazardous compounds, have to be investigated: decalcification/leaching, carbonation, and irradiation (for ILW). These tests are based on international standard procedures for cement-based matrices adopted in Romania.

SPAIN

One of the concerns regarding climatic conditions in the El Cabril area is the combination of temperature fluctuations and high RH during winter, autumn, and spring, which is especially relevant for vault walls; however, no significant impact on the waste forms is expected:

- High RH and low temperatures can favour the occurrence of microcracking owing to ice-induced damage.
- High RH + high temperatures can lead to the appearance of evaporation/condensation processes

At the El Cabril location, daily and seasonal fluctuations in temperature and RH have been related to water transport processes in disposal vaults. Due to thermal and RH variations, in the disposal vaults, evaporation and condensation cycles have been repeatedly observed inside the disposal vaults. The air gap between the containers and vault walls produced by seasonal differences leads to water vapour diffusion from the walls to the concrete containers in the summer or from the concrete containers to the walls in the winter. This results in changes in the concrete saturation and, finally, the condensation of the vapour at the cold surface of the wall vault. No significant impact on the water in contact with waste forms is expected if potential barrier failure occurs. However, this phenomenon may have a limited influence on concrete saturation and pore water chemistry until the final covers are installed.

Nowadays, in that specific geographical area, the maximum temperature can reach up to 45 °C and the minimum temperature can be as low as -5ºC (see Figure 9); however, during summer, insolation can result in an increase in temperature on the surface of the vaults, up to 55-60ºC.

Considering the long-term evolution of climatic parameters during the regulatory control period, depending on the climate scenario and the season, a rise in temperature from 2 to 6°C by 2100 is expected for Mediterranean regions according to IPCC projections, especially in the summer season. Warmer winters are foreseen, as is the concentration of yearly rainfall during that season [50], [51].

So, on the basis of a conservative climatic scenario, for thermal cycling tests, minimum and maximum temperatures will be set at -5 and 50ºC and a 60% RH (average annual value) will be considered. However, these values can be re-evaluated on the basis of the conclusions achieved in the CLIMATE work package.

In the El Cabril facility, the maximum dose rate allowed on the surface of disposal unit Ce-2a (reinforced concrete container) is 10mSv/h, which is in agreement with the maximum dose rate for the 220 L drum of 100mSv/h. Considering these boundary conditions and the 300 y-lifetime of the disposal facility, an accumulated dose rate of 1 MGy for the ageing is being considered.

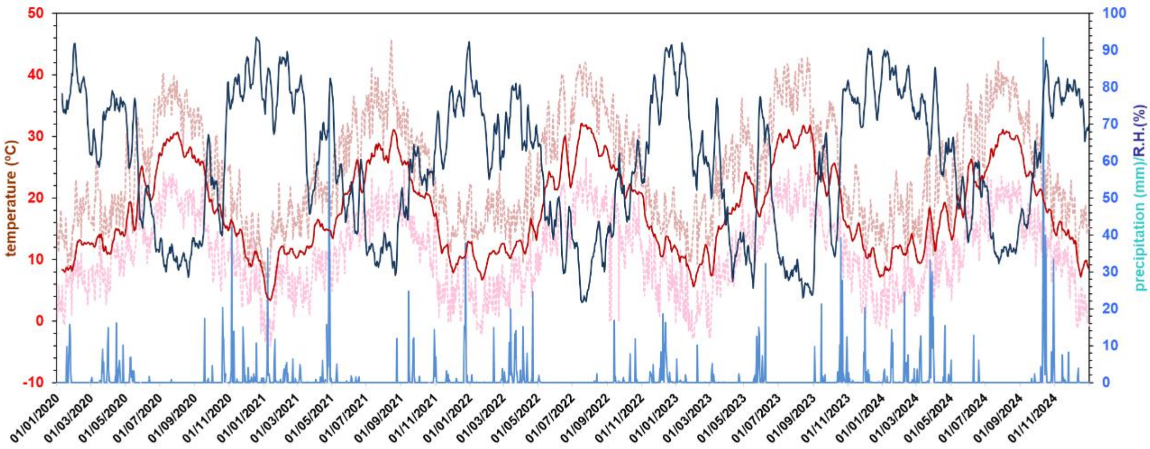

Figure 9: Temperature (max. min. average), rainfall and Relative Humidity (RH) in the El Cabril facility area during Oct'20-Oct'24.

UKRAINE

Descriptions and levels of detailed conditions are unavailable in the work instructions or operational guidelines for the disposal facility. Facility-specific WAC were developed during the initial design of the facility and form a part of the safety case. Additionally, technical specifications for waste packages were developed considering the WAC for the subsequent lifecycle stages of RWM. Regarding the aging tests, the following requirements are considered:

- Humidity (coupled with various temperatures)
- Freeze/thaw cycles
- Thermal ageing
- Carbonation effects:
- Gas generation and accumulation
- Groundwater flow
- Groundwater composition evolution
- Biodegradation resistance

In summary, when evaluating the stability of waste forms over long-term ageing, the primary environmental condition to consider is the irradiation test, which involves a cumulative dose of 1 MGy over 300 years. Following this, temperature fluctuations are the second critical environmental factor that partners plan to investigate for their impact on the durability of waste forms. One approach is to study the effects of thermal cycles, simulating seasonal temperature variations. Another approach is to examine the impact of temperatures, assuming negligible variations. Additionally, the carbonation resistance of waste forms needs to be tested for long-term ageing, particularly relevant to surface disposal facilities. Other factors to consider include humidity, precipitation, groundwater flow, gas generation, and biodegradation resistance.

5. Conclusions & Suggestions for the protocol of leaching and ageing tests

L'OPERA focuses on the study of the long-term durability of matrices and waste forms, particularly for low- and intermediate-level waste (LILW), aiming for a lifespan of 300 years. Most partners consider surface- or intermediate-depth disposal facilities, depending on their country's disposal concept. The inclusion of cementitious materials in engineered barrier systems (EBS) underscores the importance of assessing the durability performance of waste forms and matrices under cementitious pore solutions.

This clear investigative focus helps to define the most relevant material properties and environmental conditions to be considered in L'OPERA.

T3 identified and evaluated the representative conditions of disposal facilities for the long-term management of LILW in the countries involved in WP7 L'OPERA. Summarising the information collected from Section 4.1, the key parameters influencing the long-term durability of matrices and waste forms include the following:

- Chemical properties: leaching rates, chemical kinetics, pH, biodegradation, content of free liquid, ASR, active substances/reactive metals, gas production, corrosion, concentration of complexing and chelating agents, content of organics, radionuclide solubility and release, radiolysis of organic compounds, content of chemically toxic and corrosive materials, changes in macromolecular structure, and chemical structure and characteristics of the released organic by-products
- Physical properties: porosity and microporosity, specific surface, density, homogeneity, temperature, shrinkage, dustiness, internal gas pressure, microcrack generation, gas permeability, diffusion rates, dimension variation/swelling, surface dose rate, dose rate at reference distances, radionuclide content, and specific activity.
- Mechanical properties: compressive strength, flexural strength, toughness, and creep.

Additionally, the partners demonstrated a high level of agreement on the key geochemical parameters that need to be considered in leaching tests. They focus on:

- Temperature, pH, salinity, and redox conditions.

Important environmental conditions to be considered for ageing tests in L'OPERA are limited to the following:

- Irradiation (a cumulative dose of 1 MGy over 300 years), thermal cycles, temperature, carbonation, humidity, precipitation, groundwater flow, gas generation, and biodegradation resistance.

For L'OPERA, it is recommended that the design of leaching and ageing protocols be based on a normal operational phase and a monitoring phase spanning 300 years. During this period, waste is isolated from the waste packages and disposal structures to prevent the dispersion of radioactive elements into the environment. This isolation means that the contact of the cementitious pore solution with the waste forms is the most relevant process in the long term. Therefore, the cementitious pore solution should be considered for the leaching protocol, with reference protocols available such as ANSI/ANS-16.1-2019 procedure [34] and the PREDIS protocol in Appendix D. It is noteworthy that the IAEA initiated a new coordinated research project (CRP) aimed at developing a standardised approach to geopolymer waste form testing. This project seeks to contribute to sustainable, efficient, and environmentally friendly solutions for managing RW. The forthcoming technical document will serve as a valuable reference upon its release and availability.

The ageing protocol should include tests on irradiation, temperature (thermal cycles and constant temperatures), and carbonation. For irradiation tests, it is recommended that the total dose and dose rate be established based on the expected radiation exposure over the disposal period, such as a cumulative dose of 1 MGy over 300 years. For carbonation, the standard protocol outlined in EN 12390-12:2020 (1% CO_2, 20°C, 60% RH) [49] is recommended. Additionally, the importance of combined investigations of thermal cycling, irradiation, leaching, and other factors to comprehensively evaluate the long-term performance of waste forms is highlighted.

T3 provided a valuable platform for partners to share reference cases and experiences. This collaborative environment allows partners to exchange insights, best practices, and lessons learned from their projects. By leveraging this shared knowledge, partners can enhance their understanding of various methodologies and approaches, ultimately improving the quality and efficiency of their own work.

This exchange of information fosters a sense of community and cooperation, enabling partners to address common challenges and innovate.

Future research should focus on advanced material characterisation techniques to understand the microstructural changes in waste forms over time and long-term environmental impact studies to assess the interactions between waste forms and various environmental conditions. Additionally, robust modelling and simulation tools are needed to predict long-term performance under various scenarios and to extend the study over a longer period. Furthermore, field testing and long-term monitoring programs should be implemented to validate the laboratory findings. Interdisciplinary collaboration among chemists, material scientists, engineers, and environmental scientists is essential to address the multifaceted challenges of radioactive waste management and develop innovative solutions and improved waste form technologies.

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Appendix A. Questionnaire – EURAD2_WP7 L'OPERA_T3 Boundary Conditions

This questionnaire is part of the T3 Boundary Conditions EURAD2_WP7_L'OPERA, which aims to identify the key factors affecting the durability performance of waste forms and to define the long-term conditions prevailing in disposal facilities. The information generated in T3 will serve for T5 (Waste forms durability and stability testing) and T6 (implementation), defining the experimental procedures/protocols and determining the simulation scenarios.

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Q1: Are there any national requirements for the stability of waste forms regarding the chemical, physical and mechanical properties at your interest to be investigated in WP7 L'OPERA? In addition to national requirements, other properties to be investigated? Are there any durability protocols to follow?

Q2: If you do not have national requirements, what are the waste form properties in the long term of your interest to be investigated in WP7 L'OPERA? Please specify the type of waste form/matrix and provide reasons for measuring this property.

Q2.1: Chemical properties such as leaching/leakage rate, chemical kinetics, concentration of complexing and chelating agents, volume fraction of absorbent material to liquid wastes, content of chemically toxic materials, content of corrosive materials, swelling of waste forms, perturbations of the disposal system, gas production, heat production, organics, off-gas production, flammable/explosive/oxidizing, fire resistance, and waste solidification**.**

Q2.2: Physical properties such as temperature, pressure, porosity, weight/package size, and homogeneity

Q2.3: Mechanical properties such as compression resistance, drop resistance, mechanical strength, and corrosion resistance. Please specify the properties of the waste forms or packages.

Q3: Any key (geo)chemical parameters of specific interest in your disposal concept that may need to be implemented in subtask 5.2. leaching tests? for example, solution composition, pH, salinity, and redox.

Q4: Any relevant long-term environmental conditions that need to be implemented in subtask 5.1. Ageing? for example, climatic conditions (temperature fluctuation, precipitation, relative humidity), irradiation, etc.

Q5: A brief description of the national storage/disposal facility (operational and foreseen to commence in the future) and national strategy for RWM? For example, the type of repository, type of waste (I/L/VLLW), EBS system at the operative or design stage, the expected period for durability and safety cases (e.g., 300 years), interim storage before final disposal, etc.

Q6: Is there any other necessary information that needs to be considered but not mentioned above?

Appendix B. Additional information on some special LILW waste forms in the Netherlands

Some of the special LILW waste forms in the Netherlands are described below.

Depleted uranium (DU): This waste fraction represents the largest fraction of radioactive waste by mass in the Netherlands. Hence, understanding the kinetics of the reduction/oxidation and dissolution behaviour of uranium and its daughter nuclides, as well as its sorption behaviour to solid and soluble colloidal matter, is important. The principal behaviour of DU conditioned with concrete [13] for the concrete-based EBS of a disposal concept in Boom Clay [14] has been outlined in[52]. The key driver of geochemical evolution in a concrete-dominated environment is the slow degradation of cementitious materials, resulting in a high-pH alkaline plume and slowly decreasing alkaline conditions in the mid- and long-term. However, due to the complex, non-equilibrium chemistry of the different system components and the lack of reliable generation rates for colloidal particles, it is difficult to estimate the net effect on the overall radionuclide migration into the host rock. Detailed geochemical model analyses of the solubility of DU in a disposal concept in rock salt were performed in[53], but the reaction kinetics could not be addressed in sufficient detail. One important question for a rock salt environment is whether the conditioning of DU with cementitious materials is beneficial for short- and mid-term radionuclide migration, and if this is the case, which type of cementitious material is the most suitable.

Relevant chemical aspects are, in general, the chemical kinetics of U_3O_8 dissolution under conditions prevailing in a disposal situation, and the dissolution/aging behaviour of cementitious materials used in the Boom Clay (EBS) and for conditioning of the waste (rock salt).

Organic fractions in ILW: High dose rates in ILW result in the radiolysis of organic compounds. In addition to gas generation and the resulting pressure build-up (e.g., by hydrogen gas), the presence of chlorine-containing organic compounds (e.g., PVC) results in the release of corrosive products (e.g., HCl) that affect the pH and increase the corrosion rate of the waste packages[54]. Radiolysis of organic polymeric compounds can result in the release of smaller organic fragments (colloids), which may form mobile complexes with radionuclides.

The dissolution kinetics of different waste fractions, including considerations of radiolysis at high dose rates, are of general relevance for both disposal concepts. In the case of disposal in rock salt, understanding the dissolution kinetics of brucite under different chemical conditions is relevant, as brucite is used to stabilize the chemical conditions in the case of brine intrusion. Given the large number of waste containers, the corrosion rates and resulting gas generation rates are relevant for both host rocks. The solubility of radionuclides in saline solutions under different environmental conditions can only be determined with large uncertainties, and experimental support on the reaction kinetics of a number of key radionuclides under prevailing conditions is relevant in support of the Safety Case.

Ion exchange resins: resins used for the water treatment of NPP and research reactors may contain radionuclides that may be released in contact with intruding water. The high ionic strength of brines, as expected in rock salt disposal, results in a high osmotic pressure, which affects the diffuse double layer of gel-type resins with respect to its swelling behaviour and composition, and the very high ionic strength of brines may outcompete radionuclides bound to the resins.

With respect to chemical properties, the release of radionuclides in contact with brine is relevant, considering both osmotic pressure and competition with a high-salinity solution. In addition, the radiolysis of the organic resins and the impact of this radiolysis on its chemical properties, such as the generation of corrosive radiolysis products and complexing agents.

Processed molybdenum waste**:** NRG PALLAS is the world's largest supplier of medical radioisotopes. Relevant amounts of alkaline waste streams are produced during processing. Alkaline liquid wastes are conditioned with cementitious mortar and zeolites to limit the leaching of caesium[10]. The behaviour of this waste fraction under conditions present in a disposal facility in rock salt is currently uncertain. Precipitated solid waste is enclosed in a stainless steel enclosure and is currently stored as high-level waste; however, owing to its highly soluble chemical form, its behaviour in a final repository and the potential benefits of further conditioning could be of interest.

Radioactive wastes treated in a plasma oven**:** COVRA is currently running a project to construct a plasma furnace for the processing of low-level radioactive wastes, including spent ion-exchange resins. There is interest in the leaching behaviour of plasma-incinerated LILW and its subsequent durability and radionuclide release. In addition to the dissolution kinetics of different waste fractions, long-term radiolysis and the impact of radiolysis on the material are of interest.

Appendix C. National experimental procedures for novel conditioning matrices

(I) CZECH REPUBLIC

During 2004 – 2005, the properties of the geopolymer matrix were tested, and the results were summarised and incorporated into the updated Safety Assessment of the Dukovany repository. This study was dedicated to operational LLW, including spent resins and sludge, which were expected to be effectively conditioned into the geopolymer matrix.

During the experimental work, the following tests were performed:

- Compressive strength (destructive – STN 72 2117; non-destructive – EN 12 398)
- Leachability and determination of diffusion coefficients (according to ANSI/ANS-16.1-1986[55], 5, or 90 days)
- Stability after irradiation (expected cumulative dose over 300 years ≈ 1MGy)
- Matrix biodegradability
- Distribution coefficients
- Water incorporated in the matrix and freezing resistance
- Dustiness
- Strength development over time and changes in water content
- Flammability and combustion of waste

(II) FRANCE

Exploratory leaching tests of Nochar and Nochar-immobilised oils were carried out by ORANO (2022 and 2023) based on experimental protocols defined by ANDRA (national requirements basis). The hypotheses were as follows:

- Alkaline leaching solution (concrete package): The leaching solution is cementitious water representative of the CSA storage environment. – pH: 13.2+/- 0.1,
- Liquid/Solid ratio of 10 (value generally used for leaching tests),
- Continuous leaching,
- Leaching temperatures: ~20 °C (at room temperature to be representative of storage conditions) and 40 °C (at a higher temperature to accelerate phenomena).
- Measurement of total organic carbon (TOC, expressed in mg/kg dry) released in the leachates and more punctual analyses of total hydrocarbons (HCT, expressed in mg/kg dry) in the leachates.

Appendix D. Leaching protocol developed in the PREDIS project

Defined reference protocol for short-term and long-term stability testing, including minimum requirements for solution analysis and solid characterisation in the PREDIS project:

PREDIS Reference protocol		**Additional information**	**Comments, Recommendations and optional sampling etc.**
Leachant	**Synthetic cementitious water** Composition for the leachant from EURAD. "CEM I + silica fume" synthetic water (without silica)	**pH ~12.7** For 1 L: - 1.8858 g **K_2SO_4** - 0.0774 g **$CaSO_4$, 2 H_2O** - 50 ml **1 M KOH** - 950 mL Milli-Q® water	- To be made **under anaerobic conditions,** with **degassed Milli-Q® water**, additional information available in Section 2.4.
Type	**Semi-dynamic** (each step refreshing the complete volume of leaching solution)	Changing frequency: **1st year** 7 days, 14, 21, 28 d, and monthly there after **2nd year:** 14, 16, 18 months and 2 years	- Recommended use of **glove box** or **N_2-purging** of the headspace of the vessels
Sampling intervals	Modified from ISO 6961-1982; Long-term leaching testing of solidified radioactive waste forms	**1st year**: 7 days, 14, 21, 28 d, and monthly there after **2nd year**: 14, 16, 18 months and 2 years	- Shorter time spans (1 and 3 days) can be voluntarily sampled with small aliquot from liquid phase. If no replacement of the aliquot volume, max. deviation on V/SA ratio < 10%
Temperature	**22 ± 2 ° C**	Some partners will use also 40, 70 or 90 °C	- Temperature monitoring recommended
Duration	At least **90 days** (or until leaching rate has become constant) for short term studies AND **2 years** for long-term studies		
Leachant/Specimen	Volume of the leachant / exposed **"geometric" surface area of specimen" Ratio** 0.10 ± 0.02 m (= 10 cm) between leachant volume and specimen external surface area.	Ratio means e.g. 10 cm^3 of solution per 1 cm^2 of sample surface area. Ratio kept same, specimen geometry and size can vary	
Vessel	PP, PTFE or PFA (Polypropylene, Polytetrafluoroethylene, Perfluoroalkoxy alkane)	Glass vessels should be avoided with high-pH solution	
Basic techniques to be used as minimum characterization	**Solid specimen:** Density, XRD, (porosity with some method), SEM	Initial specimen, 90 d, 1 year, 2 years	- BET/MIP optional (gas adsorption techniques preferable)
	Leachant: pH, electrical conductivity, elemental concentrations (main cations)	**1st year**: 7 days, 14, 21, 28 d, and monthly there after **2nd year**: 14, 16, 18 months and 2 years. **Non filtered** samples	- Co, Ni, I, Lanthanides if present in waste. - Main anions, if possible