

# Design and Implementation of the Defense-in-Depth Concept for a Radioactive Waste Management Center in Croatia

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## ABSTRACT

This paper presents the design and technical concept of a national radioactive waste management facility in the Republic of Croatia, addressing the safe and sustainable management of institutional radioactive waste, disused sealed sources, and the Croatian share of low- and intermediate-level radioactive waste generated by the operation and decommissioning of the Krško Nuclear Power Plant.

The proposed solution is based on the establishment of a centralized waste management center at the Čerkezovac site, comprising a Central Storage Facility for institutional radioactive waste and disused sealed sources, based on the adaptation of existing structures, and a newly designed Long-Term Storage Facility for low- and intermediate-level radioactive waste. The long-term storage is designed with a capacity of approximately 2,450 reinforced concrete containers arranged in multiple layers, enabling efficient use of space and operational flexibility.

The facility is conceived as a passive storage system without on-site waste processing, where only conditioned waste packages are accepted, inspected, and stored. Operational activities include transport, receipt, verification, and periodic inspection in accordance with national, EU, and international regulatory requirements.

A key feature of the design is the implementation of the defense-in-depth safety concept, based on multiple independent engineering barriers preventing radionuclide release. These include the waste matrix, reinforced concrete containers, structural confinement, and systems for controlled collection of potentially contaminated liquids. The concept is further supported by passive ventilation, radiological monitoring, and environmental surveillance.

The proposed solution ensures a high level of radiological protection for workers, the public, and the environment, while meeting regulatory and strategic requirements. This work demonstrates a practical engineering implementation of the defence-in-depth concept in a predominantly passive storage system, providing a transferable model for similar facilities under regulatory and site-specific constraints.

**Keywords:** *Radioactive waste management, Low- and intermediate-level waste, Defense-in-depth, Passive safety systems, Engineering barriers*

## 1 INTRODUCTION

In accordance with the National Program for the Implementation of the Strategy for the Management of Radioactive Waste, Disused Sources, and Spent Nuclear Fuel (Official Gazette No. 100/18) [1] it is required to establish a long-term solution for the management of institutional radioactive waste, disused sealed sources, and its share of low- and intermediate-level radioactive waste from the Krško Nuclear Power Plant. The final location of the Radioactive Waste Management Center (hereinafter: the RWM Center) will be determined following the approval of the environmental impact assessment (EIA).

The management of radioactive waste represents a key challenge for countries with long-standing use of ionizing radiation and nuclear technologies. In the Republic of Croatia, this includes institutional radioactive waste (IRW), disused sealed sources (DSRS), and a share of low- and intermediate-level radioactive waste (LILW) generated by the operation and decommissioning of the Krško Nuclear Power Plant.

To ensure safe and sustainable management of these waste streams, the establishment of a centralized radioactive waste management facility has been defined as a central element of the national system. The proposed solution is based on the development of the RWM Center in Republic of Croatia.

The concept of the RWM Center relies on the use of existing infrastructure and the organization of the site to enable safe transport, handling, and storage of radioactive waste, while minimizing environmental impact. The facility is conceived as a storage system without on-site waste processing, accepting only conditioned waste packages suitable for long-term storage.

The design of the RWM Center follows national regulatory requirements and internationally recognized standards, particularly those of the International Atomic Energy Agency (IAEA). Special emphasis is placed on ensuring a high level of radiological protection through the application of established safety principles, including the defense-in-depth approach and the use of multiple engineering barriers.

This paper presents the design and technical concept of the RWM Center, with emphasis on the development of storage capacities for IRW, DSRS and LILW, as well as the integration of regulatory requirements, site-specific conditions, and engineering solutions into a coherent system for long-term radioactive waste management.

## **2 FACILITY DESIGN AND TECHNICAL CONCEPT**

The technical concept of the RWM Center is based on the utilization of the existing and enabling the spatial integration of storage facilities and supporting infrastructure within a controlled and functionally organized system. The design approach ensures clear separation of operational zones, controlled access, and efficient internal logistics. The total project area amounts to 475,328 m<sup>2</sup>. The spatial organization of the facility comprises:

- an entrance plateau with an administrative building and supporting infrastructure,
- a central storage zone accommodating both IRW and LILW storage facilities,
- an internal road network is designed to accommodate the transport of heavy waste packages, ensuring safe maneuvering, controlled access, and operational continuity between functional units,
- landscaped areas designed to ensure environmental integration and visual screening of the facility.

The administrative building is located at the entrance plateau, approximately 560 m from the existing entrance of the former military complex and serves as the main control and operational point of the RWM Center. The building is designed as a two-storey reinforced concrete structure accommodating administrative functions, security services, and supporting facilities. It includes spaces for visitor (Information center and Multipurpose area for exhibitions, permanent public presentations, and lectures), reception, staff offices, monitoring and control systems, and auxiliary staff areas. Controlled access to the RWM Center is established at this location, with integrated technical protection systems and supervision from the administrative building.

The storage zone is located in the central part of the site and includes two main facilities: a Central Storage Facility for institutional radioactive waste and a Long-Term Storage Facility for LILW from the Krško Nuclear Power Plant. These facilities are spatially separated but functionally integrated within the overall system.

The Central Storage Facility is based on the reconstruction and adaptation of existing semi-underground reinforced concrete structures originally designed for military use. These structures are

repurposed for the reception and storage of IRW and DSRS, enabling consolidation of waste currently stored at multiple locations within the Republic of Croatia.

The Long-Term Storage Facility is designed as a new reinforced concrete structure intended for the storage of LILW in conditioned form. The facility is planned with a storage capacity of approximately 2,450 reinforced concrete containers, arranged to ensure efficient use of space and operational flexibility.

The internal transport system is based on an upgraded road network designed along existing routes, enabling safe and controlled movement of radioactive waste packages between functional zones. The road network includes primary and secondary access routes, manoeuvring areas for transport vehicles, and dedicated access to storage facilities.

Supporting infrastructure systems include water supply and drainage networks, electrical power supply, technical protection systems, and environmental control measures. These systems are designed to ensure reliable operation, environmental protection, and compliance with applicable regulatory requirements.

The project includes both reconstruction of existing infrastructure and construction of new facilities, covering all functional components required for the operation of the RWM Center. The main elements of the project include:

- reconstruction of existing buildings for the Central Storage Facility for IRW and DSRS;
- construction of a new Long-Term Storage Facility for LILW;
- construction of an administrative building and entrance plateau;
- reconstruction and upgrading of access and internal roads;
- construction of auxiliary facilities within the storage area;
- construction of water supply infrastructure, including pumping stations and reservoirs;
- construction of electrical substations and supporting energy systems.

The facility is designed as a storage-based system in which radioactive waste is received in conditioned form, verified upon arrival, and stored under controlled conditions. Operational activities include transport, receipt, inspection, placement, and periodic monitoring of waste packages. The overall design integrates spatial planning, infrastructure systems, and operational requirements into a coherent technical solution, providing the basis for safe and efficient long-term management of radioactive waste in the Republic of Croatia. In addition to meeting national regulatory requirements, the design is aligned with internationally recognized safety standards, particularly those established by the IAEA, including General Safety Requirements (GSR) Part 5 [2] and Specific Safety Requirements (SSR-5) [3].

The main contribution of this work lies in the integration of regulatory requirements, site-specific conditions, and engineering design into a coherent and implementable concept for a centralized radioactive waste storage facility, with particular emphasis on the practical implementation of the defense-in-depth principle in a predominantly passive storage system. An additional contribution is the adaptation of existing military infrastructure into a compliant radioactive waste storage facility, demonstrating an efficient approach to infrastructure reuse under stringent safety requirements.

Since Long term facility and Central storage facilities represent the most important parts of the site, they are described in a more detail within following chapters of this paper.

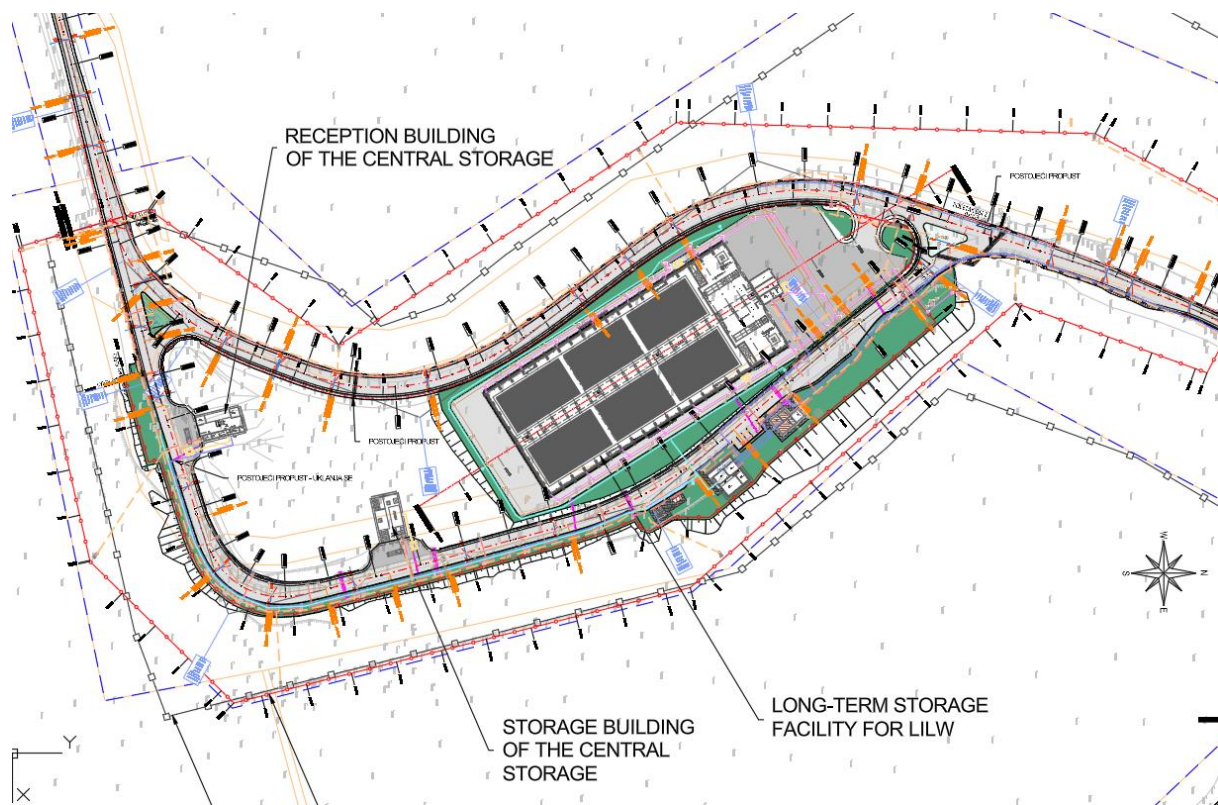


Figure 1: Site plan of Long-term Storage and Central Storage

### 3 LONG-TERM STORAGE FACILITY

#### 3.1 General Description

The Long-Term Storage Facility is designed as a new reinforced concrete structure intended for the storage of LILW generated by the Krško Nuclear Power Plant. The facility has a total area of approximately 6,400 m<sup>2</sup> and is designed to accommodate approximately 2,450 reinforced concrete containers (RCC), arranged in multiple layers to ensure efficient use of space and operational flexibility. The final number and arrangement of containers depend on the selected RCC type. The total activity of the stored LILW is estimated at approximately  $1 \times 10^{13}$  Bq.

The facility is conceived as a single-volume storage hall with an annex containing auxiliary and operational spaces. The annex includes a control room, equipment storage, and areas for personnel monitoring and decontamination. A dedicated traffic area is provided in front of the facility to enable controlled access and maneuvering of transport vehicles. Delivery vehicles enter the facility in reverse, ensuring full positioning within the storage hall during unloading operations.

#### 3.2 Functional Layout

The building consists of two structurally separated units:

- The main storage hall;
- The annex with control, decontamination, and support spaces.

The layout includes:

1. RCC storage area
2. Protective concrete wall
3. Area for RCCs not meeting acceptance criteria
4. RCC inspection and measurement area
5. Control room for monitoring delivery and storage processes

6. Equipment storage
7. Personnel contamination monitoring
8. Personnel decontamination facilities

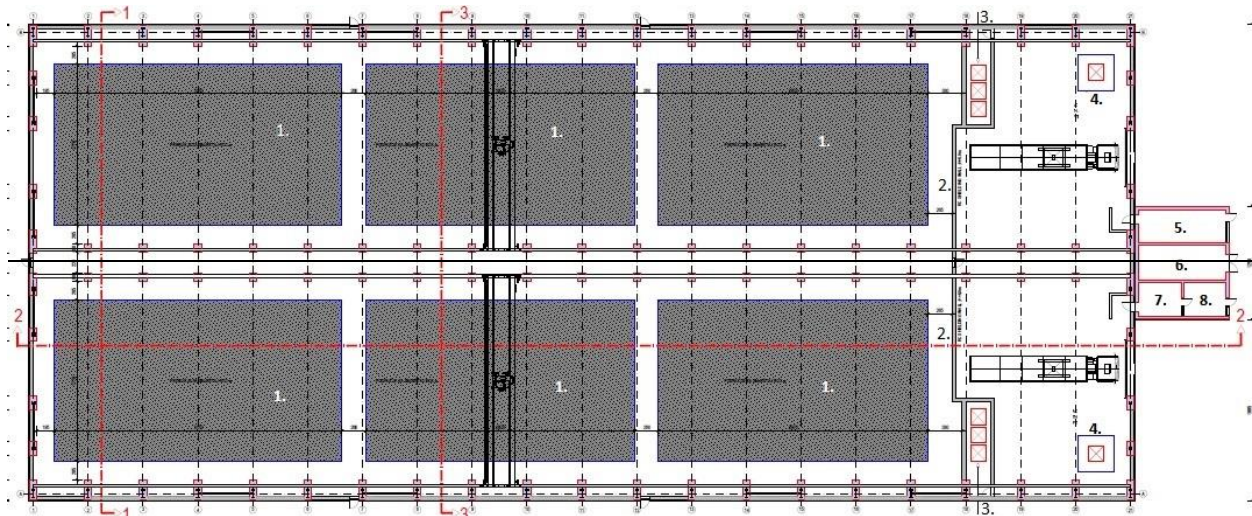


Figure 2: Layout of the Long-term storage

The storage hall is divided into two longitudinal sections, enabling independent operation and improved handling efficiency. The inspection and measurement area is located near the vehicle access points, allowing immediate verification of delivered waste packages before storage. Non-compliant containers are temporarily stored in a designated area, physically separated from the main storage zone. Personnel movement within the annex follows a controlled one-way flow from potentially contaminated to clean areas, ensuring radiological protection and minimizing cross-contamination.

### 3.3 Handling and Storage Process

The handling and storage process is designed to ensure compliance with waste acceptance criteria and to minimize radiological exposure and handling-related risks. Waste packages are delivered to the facility in RCC and undergo a defined acceptance procedure prior to storage.

Upon delivery, each RCC is subject to:

- verification of documentation,
- visual inspection of structural integrity,
- dose rate measurement (at surface and at 1 m distance),
- surface contamination monitoring.

Containers that meet the waste acceptance criteria (WAC) are transferred to designated storage positions, with all relevant data recorded for traceability. Non-compliant containers are temporarily stored in a dedicated area until further action is taken. RCCs are stored in rows arranged across three vertical levels within the storage hall. The final configuration depends on container type and handling requirements. Handling operations are performed using overhead crane systems, allowing safe and controlled lifting, transport, and placement of containers.

The operational process includes two main phases:

- reception phase (delivery, inspection, and placement),
- storage phase (no reception activities, periodic inspection only).

The maximum delivery rate is limited to four RCCs per day, ensuring controlled and manageable operational conditions.

### 3.3.1 Reinforced concrete containers

LILW is conditioned in RCCs, which represent a key component of the storage system.

RCCs are designed to contain waste packages (e.g., drums or compacted waste forms) embedded in a cementitious matrix, with voids filled using binding materials to ensure structural stability and radionuclide confinement.

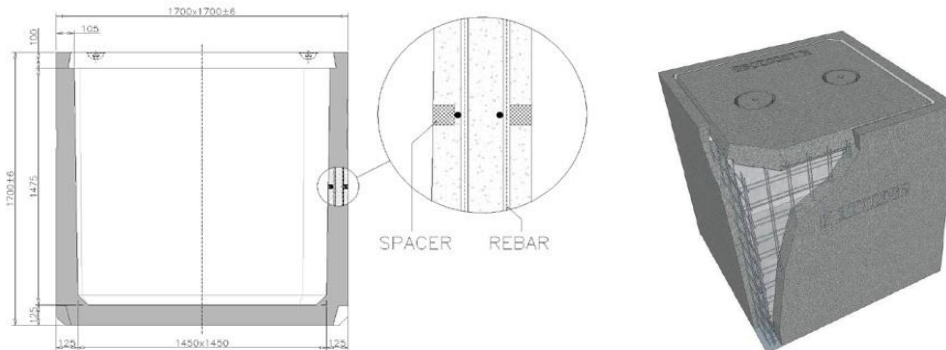


Figure 3: RCC model

Three RCC types are considered, differing in dimensions and mass, with maximum weights ranging from 15,000 kg to 20,000 kg.

## 3.4 Technological Systems

The following systems are implemented to support safe handling, environmental control, and operational reliability of the facility.

### 3.4.1 Overhead Crane System

The facility is equipped with two overhead cranes, each with a span of approximately 23 m, a load capacity of up to 25 tonnes, and a lifting height of approximately 10 m. The cranes operate primarily via remote control (radio control with camera support), with manual pendant control available as a backup mode. The use of two cranes enables simultaneous operations in separate sections of the storage hall.

### 3.4.2 Ventilation System

Ventilation is based on a passive system using fixed louvers installed along the building perimeter. These are complemented by motorized ON/OFF louvers equipped with position sensors. Continuous air exchange is achieved through distributed openings, while emergency conditions allow for rapid closure of ventilation openings via a centralized control system. Local HVAC systems are installed in operational areas to ensure suitable working conditions for personnel.

### 3.4.3 Drainage and Contaminated Liquid Management

A dedicated drainage system is designed as a conservative safety measure for emergency conditions (e.g., spills, fire, aircraft impact). The system includes:

- two collection sumps connected to the storage area,
- one separate sump for the decontamination area.

All sumps are designed as reinforced concrete structures with integrated stainless steel tanks, enabling monitoring of liquid levels and radioactivity. Collected liquids are retained and managed by an authorized service provider.

#### 3.4.4 Fire Protection System

Fire protection is provided through portable and mobile dry powder extinguishers, as well as an internal hydrant network within defined fire compartments.

### 3.5 Structural Design

The Long-Term Storage Facility is designed as a single-storey structure combining reinforced concrete and steel construction. The reinforced concrete part forms the foundation slab and structural walls, providing load-bearing capacity, radiation shielding, and confinement. The upper structure consists of a steel roof system, enabling large-span coverage of the storage hall and unobstructed internal space for handling operations. Structural stability is ensured through the combined action of reinforced concrete elements and steel bracing systems, designed to resist vertical and horizontal loads, including seismic effects. The structure supports overhead crane systems and ensures safe, reliable, and efficient operation of the facility.

## 4 CENTRAL STORAGE FACILITY

### 4.1 General Description

The Central Storage Facility is intended for the reception and storage of IRW and DSRS generated within the Republic of Croatia. The facility is based on the reconstruction and repurposing of two existing semi-underground reinforced concrete structures of type U-20, originally designed for military storage. The total usable area of a single U-20 storage unit is 209 m<sup>2</sup>. The selected structures are located approximately 100 m apart and are connected by an internal access road.

The facility comprises two functionally separate units:

- a Reception Building for inspection, verification, and acceptance of waste packages,
- a Storage Building for long-term storage of accepted waste.

The storage concept is based on a passive approach, where only conditioned waste is accepted and no treatment or conditioning activities are performed on-site.

### 4.2 Functional Layout and Storage Concept

The Reception Building is designed to enable controlled acceptance and verification of IRW and DSRS prior to storage. Upon delivery, waste packages undergo inspection, radiological measurements, and documentation verification to confirm compliance with WAC. Processing and conditioning of waste will not be performed within the RWM Center.

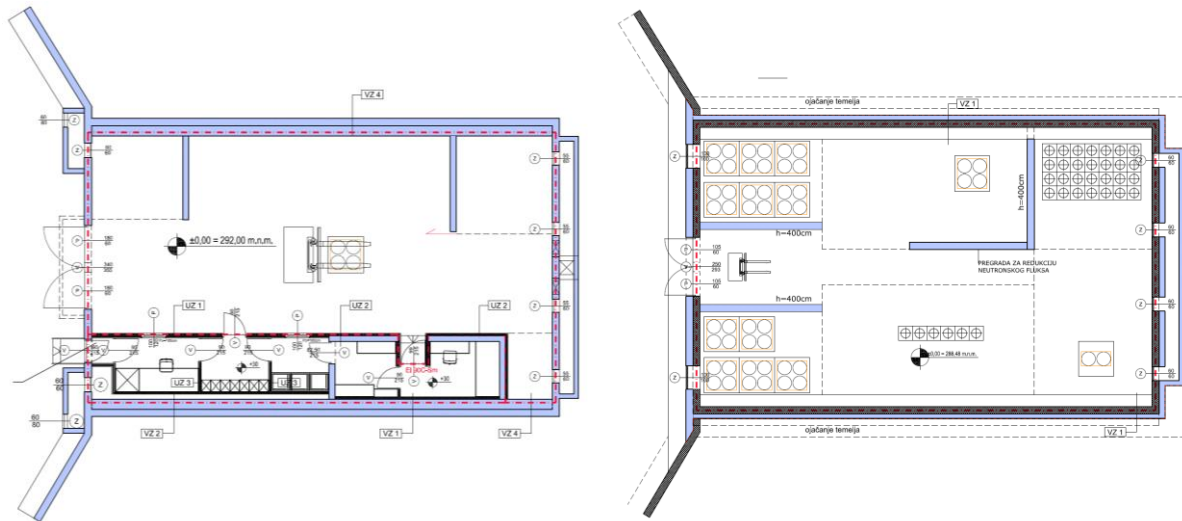


Figure 4: Central Storage layout - Reception Building (left) and Storage Building (right)

If required, personnel decontamination is performed in a physically separated area, with controlled collection of potentially contaminated liquids. The Storage Building is organized into zones according to the type and hazard level of radioactive waste. Waste is stored progressively deeper into the facility:

- the front section is designated for short-lived radioactive waste,
- the central section for higher activity sealed sources and radioactive materials,
- the rear section for neutron sources and very high-activity sources.

These zones are separated by internal partitions to reduce radiation exposure and ensure safe operation. No permanent workplaces are planned within the storage facility.

### 4.3 Handling and Operational Process

Waste packages are delivered to the Reception Building, where unloading is performed using appropriate handling equipment, including forklifts for heavier packages.

Each package is subject to:

- visual inspection (integrity check),
- dose rate measurement (surface and at 1 m distance),
- surface contamination monitoring,
- verification of accompanying documentation.

Packages meeting WAC requirements are temporarily held and subsequently transferred to the storage building. Transport to the storage facility is performed periodically, with storage campaigns planned up to twice per year. This controlled process ensures traceability, limits unnecessary handling, and supports radiological safety during both operational phases.

### 4.4 Technological Systems

#### 4.4.1 Ventilation System

Ventilation of both receiving and storage buildings is based on a passive system using fixed and motorized louvers. Air intake is provided through façade openings, while exhaust air is discharged through existing ventilation channels. In emergency conditions, ventilation openings can be closed via an emergency shutdown system. The Reception Building is additionally equipped with local HVAC systems to ensure appropriate working conditions in occupied spaces.

#### 4.4.2 Drainage and Contaminated Liquid Management

A drainage system is provided as a conservative safety measure for emergency situations.

The system includes separate collection tanks for:

- the Reception Building (including decontamination area),
- the Storage Building.

Collection tanks are designed as reinforced concrete basins with integrated stainless steel vessels, enabling monitoring and controlled retention of potentially contaminated liquids.

#### 4.4.3 Monitoring Systems

The facility includes systems for:

- dose rate monitoring in both receiving and storage areas,
- radon concentration monitoring within the storage building.

These systems support radiological protection and enable early detection of abnormal conditions.

#### 4.4.4 Fire Protection System

Fire protection is ensured through portable dry powder extinguishers and an internal hydrant network.

### 4.5 Structural Design

The Central Storage Facility is based on the reconstruction and structural upgrading of existing semi-underground reinforced concrete structures originally designed for military storage. These structures consist of arched reinforced concrete shells with significant soil cover, providing inherent shielding and thermal stability, which is advantageous for radioactive waste storage. As part of the conversion to radioactive waste storage, structural rehabilitation measures are implemented, including remediation of waterproofing systems, repair of moisture-affected concrete, and local structural strengthening, ensuring long-term durability and confinement performance. Since the original structures do not meet current seismic requirements, additional strengthening measures are introduced to achieve compliance with Eurocode standards and ensure structural safety. Internal reconfiguration enables functional separation of storage zones and enhances radiological protection. The upgraded concept preserves the advantages of the original design while ensuring compliance with modern safety requirements.

## 5 SAFETY CONCEPT AND DEFENSE-IN-DEPTH IMPLEMENTATION

### 5.1 General Safety Concept

The safety concept of the RWM Center is based on the principle of defence-in-depth, implemented through engineered barriers supported by safety systems. The design prioritizes passive safety by relying on the inherent properties of waste forms, containment systems, and structural elements to ensure long-term confinement of radionuclides with minimal dependence on active systems.

Defence-in-depth is achieved through multiple independent and redundant barriers, ensuring that failure of a single barrier does not lead to uncontrolled release of radionuclides. In addition to engineered barriers, supporting systems contribute to the fulfilment of the fundamental safety functions: prevention of radionuclide release, monitoring of system conditions, and mitigation of potential consequences. The concept is adapted to each facility: the Long-Term Storage Facility applies a four-barrier system associated with conditioned waste and reinforced concrete containers, while the Central Storage Facility applies a simplified barrier system consistent with the

characteristics of institutional radioactive waste and existing storage structures. The overall safety performance of the system is verified through safety assessments [4], demonstrating compliance with regulatory dose limits for workers and the public.

## **5.2 Engineered Barriers – Long-Term Storage Facility**

The defense-in-depth concept for the Long-Term Storage Facility is implemented through four engineered barriers, designed to ensure containment of radionuclides under both normal and abnormal conditions.

These barriers correspond directly to the storage concept described in Section 3, including the use of RCCs and controlled drainage systems.

The safety concept of the Long-Term Storage Facility is based on a multi-barrier approach comprising the following engineered barriers:

1. Waste matrix (conditioned LILW)

The primary barrier consists of immobilized LILW embedded in a cementitious matrix and contained within internal packages (e.g., metallic drums, compacted waste forms, and/or ingots). The cementitious matrix ensures waste stabilization, reduces radionuclide mobility, and provides initial containment by limiting leaching and dispersion processes. This reduces radionuclide mobility at the source.

2. Reinforced Concrete Container

The RCC serves as a secondary barrier, providing mechanical strength, radiation shielding, and additional confinement. The RCC prevents the release and migration of radionuclides under normal operating and storage conditions, while contributing to structural integrity and ensuring compatibility with handling and storage.

3. Storage building structure

The reinforced concrete structure of the Long-Term Storage Facility constitutes an additional confinement barrier. Although not designed as a hermetically sealed system, the structure significantly limits atmospheric releases through controlled ventilation and restricted leakage pathways. It also provides shielding and protection against external hazards while maintaining a simple and inherently stable design.

4. Drainage system with collection sumps

A dedicated drainage system, incorporating three collection sumps, ensures the controlled collection, monitoring, and retention of potentially contaminated liquids. This system is particularly relevant under abnormal or accident conditions (e.g., spills, firefighting water), preventing uncontrolled releases to the environment.

For atmospheric release pathways, protection is ensured by the sequential action of barriers (1), (2), and (3). For liquid release pathways, the relevant barriers are (1), (2), and (4), acting in the same order.

## **5.3 Engineered Barriers – Central Storage Facility**

In the Central Storage Facility, the defense-in-depth concept is adapted to the characteristics of institutional radioactive waste and the structural configuration of repurposed storage buildings described in Section 4.

The barrier system reflects the passive storage approach and the absence of complex conditioning systems, resulting in a simplified safety concept tailored to institutional radioactive waste.

In the case of the Central Storage Facility, the safety concept is based on the implementation of the following three engineered barriers:

1. Waste packaging (metal containers and certified packages).

The primary barrier consists of metallic storage containers used for the confinement of radioactive waste. These include 200-litre drums containing LILW, as well as metallic

capsules containing disused sealed sources. The latter are stored in certified Type A packages designed for gamma and neutron sources, ensuring adequate containment, shielding, and safe handling during storage and transport operations.

2. Storage building structure

The semi-underground reinforced concrete structures provide physical confinement, shielding, and environmental protection. Although not airtight, the structures significantly reduce the potential for atmospheric releases.

3. Drainage system with collection sump

A dedicated drainage system enables controlled collection and retention of potentially contaminated liquids in both receiving and storage buildings.

For atmospheric release pathways, barriers (1) and (2) are dominant, while for liquid release pathways, barriers (1) and (3) are relevant.

## 5.4 Systems Important for Radiological Safety

In addition to engineered barriers, the safety concept is supported by systems that ensure monitoring, prevention, and mitigation of potential radiological hazards.

The systems important for the radiological safety of the RWM Center can be functionally grouped as follows:

Monitoring systems, which provide continuous or periodic assessment of radiological conditions in order to detect deviations from normal operation:

- Environmental dose rate monitoring system;
- Indoor dose rate monitoring system within storage facilities;
- Radon concentration monitoring system in the Central Storage Facility;
- Radiological monitoring system for potentially contaminated liquids.

Prevention systems, which are designed to prevent the occurrence of incidents or limit their likelihood:

- Passive ventilation isolation system in storage facilities;
- Crane safety systems installed on overhead bridge cranes, preventing accidental dropping of RCCs during handling;
- Horizontal and vertical traffic signalling system for safe and controlled movement within the Center.

Mitigation and protection systems, which reduce the consequences of potential incidents and provide protection of personnel, the public, and the environment:

- Fire detection and fire protection system;
- Drainage and liquid collection control (through monitored systems associated with liquid management);
- Physical protection system, including technical security and access control measures.

Support systems, which ensure the reliable operation of safety-related functions under all conditions:

- Backup power supply system, ensuring uninterrupted operation of safety-important systems in the event of loss of off-site power.

These systems contribute to the defense-in-depth concept by enabling early detection of abnormal conditions, supporting prevention of unintended exposure, and mitigating potential consequences, thereby complementing the engineered barrier system.

## 5.5 Passive and Active Systems

The systems implemented at the RWM Center are classified as passive or active based on their role in fulfilling the fundamental safety functions: prevention of radionuclide release, monitoring of system conditions, and mitigation of potential consequences.

Passive systems rely on inherent physical properties and design features and do not require external power or operator action, contributing to intrinsic safety and long-term reliability. Active systems involve monitoring, control, or mechanical operation and provide early detection of deviations and controlled response under abnormal conditions.

Together, these systems complement the engineered barriers and ensure that key safety functions are maintained under both normal and abnormal conditions.

#### 5.5.1 Long-Term Storage Systems

Long-Term Storage Facility is equipped with systems that support safe handling of RCCs, maintain stable environmental conditions, and enable monitoring and response in case of abnormal events.

- Overhead crane systems  
These systems ensure safe and controlled handling of heavy RCCs, thereby reducing the likelihood of mechanical damage to waste packages and preventing potential loss of confinement during handling operations.
- Passive ventilation system  
The ventilation system contributes to maintaining stable environmental conditions within the storage facility and limits the potential for airborne dispersion of radionuclides. The capability to isolate ventilation openings in emergency conditions further reduces the risk of uncontrolled atmospheric releases.
- Drainage system with collection sumps  
The drainage system provides controlled collection and retention of potentially contaminated liquids in accident scenarios (e.g., spills or fire events), preventing their uncontrolled release into the environment and enabling radiological monitoring prior to further management.
- Monitoring systems  
Radiological and environmental monitoring systems provide continuous surveillance of internal conditions, enabling early detection of abnormal radiation levels or environmental deviations and supporting timely operational response.
- Fire protection system  
The fire protection system limits the consequences of fire events by enabling rapid initial response, thereby reducing the risk of damage to waste packages and preventing secondary radiological impacts.

#### 5.5.2 Central Storage Systems

The systems implemented in the Central Storage Facility reflect the characteristics of institutional radioactive waste and the use of existing storage structures, with emphasis on simplicity, robustness, and controlled operation.

- Drainage system with collection sumps  
This system ensures controlled collection and retention of potentially contaminated liquids in abnormal situations, preventing environmental release and enabling monitoring and controlled handling.
- Passive ventilation system  
The ventilation system supports the maintenance of acceptable internal conditions and reduces the potential for airborne contamination, while emergency closure capability limits possible atmospheric releases.
- Monitoring systems  
Dose rate and radon monitoring systems ensure continuous control of radiological conditions within the facility, supporting worker protection and enabling early identification of deviations from expected conditions.

- Fire protection system  
The fire protection system mitigates the consequences of fire events, reducing the likelihood of damage to waste packages and limiting potential radiological hazards.

### 5.5.3 Shared Systems

In addition to facility-specific systems, several systems are implemented at the level of the RWM Center to support overall safety and ensure protection of the public and the environment.

- Radiological monitoring system  
The environmental monitoring network provides continuous surveillance of radiation levels around the site, enabling early detection of abnormal releases and supporting protection of the public.
- Physical protection system  
Controlled access and zoning prevent unauthorized entry and reduce the likelihood of malicious or unintended interference with safety-related systems and stored waste.
- Technical protection system  
Surveillance and alarm systems ensure continuous monitoring of the site and enable rapid response to security-related events.
- Fire protection infrastructure  
Site-wide fire protection systems provide enhanced capability for fire detection and suppression, limiting the potential escalation of fire events and associated radiological consequences.
- Backup power supply system  
The backup power supply ensures continued operation of safety-relevant monitoring and control systems in the event of loss of off-site power, maintaining the availability of key safety functions.

The combined implementation of passive and active systems ensures that key safety functions prevention, monitoring, and mitigation are maintained under both normal and abnormal conditions. Together with engineered barriers, these systems form an integral part of the defence-in-depth concept, ensuring a robust and reliable safety framework for long-term radioactive waste management.

## 6 CONCLUSION

This paper presents the design and safety concept of a centralized RWM Center in the Republic of Croatia for the management of IRW, DSRS, and LILW.

The proposed solution is based on a storage-oriented approach without on-site processing, relying on conditioned waste forms, reinforced concrete containment systems, and robust structural design. The implementation of the defence-in-depth concept through multiple independent engineered barriers ensures effective confinement of radionuclides under both normal and abnormal conditions.

A key feature of the design is the prioritization of passive safety, reducing dependence on active systems while enhancing long-term reliability and robustness. Active systems are implemented in a complementary role, providing monitoring and response capabilities that support the fundamental safety functions of prevention, monitoring, and mitigation.

The main contribution of this work is the demonstration of a practical engineering implementation of the defence-in-depth concept in a predominantly passive storage system, adapted to site-specific conditions and regulatory requirements. The integration of existing infrastructure, regulatory constraints, and engineering design into a coherent and implementable solution represents a viable model for similar storage-based radioactive waste management systems.

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