

RD&D Program for joint SNF and HLW Disposal in Deep Geological Repository in the Republic of Croatia or in the Republic of Slovenia

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ABSTRACT

The Research, Development, and Demonstration (RD&D) Program for joint Spent Nuclear Fuel (SNF) and High-Level Radioactive Waste (HLW) Disposal in Deep Geological Repository (DGR) in the Republic of Croatia (RC) or in the Republic of Slovenia (RS) was prepared in the frame of the Fourth revision of the Krško NPP Radioactive Waste and Spent Nuclear Fuel Disposal Program. The RD&D Program was commissioned by the Croatian Fund for financing the decommissioning of the Krško NPP and the disposal of radioactive waste and SNF (the Fund), and the Slovenian Agency for Radioactive Waste Management (ARAO), in accordance with national regulations and strategic documents of both countries. The Program was developed by an international consortium of Croatian, Slovenian and Czech research institutions and companies.

Based on the Intergovernmental Agreement between the Republic of Croatia and the Republic of Slovenia, both countries are obliged to ensure the safe long-term disposal of their respective shares of SNF and HLW generated by the operation and decommissioning of the Krško NPP. National strategies envisage disposal of SNF and HLW in a deep geological repository (DGR) located either in Croatia or Slovenia, with the alternative option of disposal in an international repository.

The RD&D Program provides a comprehensive framework for implementing this objective, including a review of previous research, development of site selection criteria, proposal of technologies and methodologies, a phased timeline, pre-operational monitoring, stakeholder engagement strategies, and cost estimates for program implementation. The site selection process will be multidisciplinary, combining desk studies, laboratory and field investigations, as well as economic and sociological studies and analyses.

Keywords: *RD&D, DGR, SNF, Site selection criteria*

1 INTRODUCTION

The management of High-Level Radioactive Waste (HLW) and Spent Nuclear Fuel (SNF) represents one of the most technically complex and socially sensitive challenges in modern energy policy. For the Republic of Croatia and the Republic of Slovenia, this challenge is amplified by the unique case of the jointly owned and operated Krško Nuclear Power Plant (KNPP), a 696 MWe pressurized water reactor located in Slovenia that produces and supplies equal shares of electricity to both countries.

Under the Intergovernmental Agreement between the Government of the Republic of Slovenia and the Government of the Republic of Croatia on the Regulation of the Status and Other Legal Relations Regarding the Investment, Exploitation and Decommissioning of the Krško NPP (OG of RC – Intergovernmental Agreements, No. 9/2002 and OG of RS – Intergovernmental Agreements No. 5/03), (Intergovernmental agreement), both countries share equal responsibility for the safe disposal of all radioactive waste and spent fuel generated by the KNPP throughout its operational lifetime and during decommissioning. The KNPP is currently licensed for operation until 2043, with discussions regarding potential life extension underway.

A joint RD&D Program was commissioned in response to obligations under EU Council Directive 2011/70/Euratom on the responsible and safe management of spent fuel and radioactive waste, and in alignment with both countries' national regulatory programs. The Program was developed by a six-institution consortium comprising the Croatian Geological Survey (HGI-CGS), the University of Zagreb Faculty of Mining, Geology and Petroleum Engineering (FMGPE), Consensus d.o.o., the Slovenian National Building and Civil Engineering Institute (ZAG), the Geological Survey of Slovenia (GeoZS), and the Czech Geological Survey. This paper presents the Program's methodology, principal findings, and proposed actions.

1.1 Regulatory and Strategic Framework

The legal basis for the joint RD&D Program are defined by the Intergovernmental Agreement, Croatian national legislation including the Radiological and Nuclear Safety Act (OG of RC, No. 141/13, 39/15, 130/17, 118/18, 21/22), The Radioactive Waste, Disused Sources and Spent Nuclear Fuel Management Strategy (OG of RC No. 125/14) and the National Program for the Implementation of the Radioactive Waste, Disused Sources and Spent Nuclear Fuel Management Strategy (Program for the period until 2025 with a view until 2060) (OG of RC Nos. 100/18 and 156/22), and Slovenian legislation including the Ionising Radiation Protection and Nuclear Safety Act (OG of RS, No. 76/17, 26/19, 172/21) and Resolution on the National Program for Managing Radioactive Waste and Spent Nuclear Fuel 2023-2032 (OG of RS No. 14/23).

A dual-track approach is envisioned by the strategic documents of both countries: primary development of a national mined DGR sited in either Croatia or Slovenia, with the parallel option of participating in a multinational repository if such a facility becomes available within the European territory, as well as the possibility of alternative disposal technology – Deep Borehole Disposal.

Besides existing national legislation, bilateral agreement between the two countries, the development of the RD&D Program is based on relevant international conventions regulating nuclear safety and radioactive waste management and guidelines, particularly safety standards and technical guidelines issued by the International Atomic Energy Agency (IAEA).

1.2 Waste Inventory

Two operational scenarios define the inventory of waste requiring disposal. Under the Baseline Case Scenario (BCS), assuming KNPP shutdown in 2043, a total of 2,282 spent fuel assemblies, containing approximately 926,5 t of heavy metal (HM), will require geological disposal. Additional waste considered for disposal includes 140 t of decommissioning HLW (reactor internals), ~550 t of radioactive waste (RW) from the decommissioning of SNF dry storage, and

~172 m³ of encapsulation facility waste, while repository operational waste is expected to be minimal. An Extended Lifetime Sensitivity Case (ELSC) considers plant operation to 2063, the inventory increases to 3,182 fuel assemblies containing 1,291.9 t of HM, with corresponding increases in dry storage and encapsulation facility decommissioning waste.

2 SITE SELECTION CRITERIA

The development of site selection criteria for the joint RD&D Program is based on IAEA recommendations, existing regulatory frameworks in Croatia and Slovenia, and experience from countries with advanced geological disposal programs. The criteria presented here represent a preliminary methodological framework and do not constitute official regulatory requirements. Harmonized criteria will need to be formally defined and adopted within the national regulatory systems of both countries.

In accordance with international practice, site selection criteria are divided into exclusionary and comparative criteria. **Exclusionary criteria** are applied to eliminate unsuitable areas where geological, environmental, or societal conditions would compromise repository safety or feasibility. These criteria typically address issues such as tectonic instability, resource conflicts, unfavourable hydrogeological conditions, or external hazards.

Comparative criteria are used to evaluate and rank remaining candidate areas and sites based on geological suitability, environmental considerations, technical feasibility, and socio-economic factors. In some programs, these criteria are further divided into discretionary criteria—associated with attributes relating to issues, events, hazards and other considerations for which protective engineering solutions exist—and ranking criteria, which are used for comparative evaluation of candidate sites.

The criteria are applied progressively through multiple siting phases, including regional screening, identification of suitable areas, selection of potential sites, and evaluation of candidate sites. Their application is subject to several constraints, including site-specific data availability, the host rock type, and repository design considerations. Certain parameters (e.g., hydrogeological, geomechanical, and geochemical properties) can only be reliably determined following detailed site investigations, including drilling and underground research facility development.

The criteria are structured into three main groups:

- **Geological criteria**, focusing on geological processes, properties and hazards;
- **Natural resource and anthropogenic impacts**, addressing potential human intrusion and competing land uses;
- **Environmental and societal criteria**, considering population, infrastructure, environmental protection, and public acceptance.

Each criterion is expressed at three appraisal levels: Desirable, Conditionally Desirable, and Undesirable. A multi-criteria decision analysis (MCDA) methodology is proposed for ranking and selecting the most suitable sites. The overall framework is designed to be implemented within a Web Geographic Information System (WebGIS) technology, enabling transparent, reproducible, and auditable site comparisons.

The overall objective is to identify geological environments that ensure long-term isolation and containment of radioactive waste through a robust combination of natural and engineered barriers. Preference is given to stable, homogeneous formations with low permeability, favourable geochemical conditions, and minimal or no exposure to natural hazards or human activities.

2.1 Methodology for Assessing Compliance Across Siting Phases

Compliance with Program requirements is evaluated at the end of each siting phase through defined outputs, data quality, and alignment with safety objectives. As the process advances,

analyses become progressively more detailed and form an integral part of the evolving safety case. All data and results must be transparent and publicly accessible.

Typical outputs include spatial datasets and maps, geological and geotechnical models, stakeholder engagement outcomes, identification of constraints, and inputs for subsequent phases.

The methodology follows a stepwise refinement approach:

- **Initial survey of the territory of both countries (RS & RC):** Application of exclusionary criteria using existing datasets to identify suitable regions via GIS-based analysis.
- **Narrowing of suitable regions:** Further exclusionary screening with improved spatial resolution to define suitable subregions.
- **Screening for suitable areas:** Introduction of comparative criteria alongside exclusionary ones to identify suitable areas (~400 km²), supported by targeted field verification.
- **Selection of potential sites:** Integration of detailed datasets and limited field investigations to define ~20 potential sites (~5 km²), supported by preliminary geological and hydrogeological models.
- **Selection of candidate sites:** Advanced site characterization, including higher-resolution mapping and possible exploratory drilling, to select one candidate site per country and refine conceptual and numerical models.
- **Site confirmation:** Final verification through detailed investigations and integration into a comprehensive safety case.

A significant aspect of decision-making in these steps is determining when to implement the volunteering principle. It can be suggested that the “call for volunteers” be issued after Step 3, when suitable areas—and thus municipalities within them—have been identified, or after Step 4, when potential sites have been identified (Figure 1).

PROGRAM DEVELOPMENT TIMELINE		STEP	1. INITIAL SURVEY OF TERRITORY OF BOTH COUNTRIES	2. NARROWING OF SUITABLE REGIONS	3. SCREENING FOR SUITABLE AREAS			4. SELECTION OF POTENTIAL SITES			5. SELECTION OF CANDIDATE SITES								
		STEP RESULT	SUITABLE REGIONS	SUITABLE SUBREGIONS	SUITABLE AREAS			POTENTIAL SITES			CANDIDATE SITES								
CRITERIA GROUP	CRITERIA SUBGROUP	CRITERIA	Exclusionary	Exclusionary	Exclusionary	Comparative		W.F.	Exclusionary	Comparative		W.F.	Exclusionary	Comparative		W.F.			
						Discretionary	Ranking			1-10	Discretionary			Ranking	1-10		Discretionary	Ranking	1-10
1. GEOLOGICAL CRITERIA: PROCESSES, PROPERTIES AND HAZARDS	1.1. IMPACT OF FUTURE GEODYNAMIC CHANGES	1.1.1. Climate change – glaciation																	
		1.1.2. Erosion			x				10	x			10	x				10	
		1.1.3. Future tectonics								x			10				x	10	
		1.1.4. Neotectonics				x			10			x	8						
		1.1.5. Active fault zones	x	x	x				10	x			10				x	10	
		1.1.6. Fissure systems								x			10	x				10	
		1.1.7. Seismicity			x				10			x	8				x	8	
		1.1.8. Volcanism	x																
		1.1.9. Geothermal gradient and thermal springs								x			10				x	9	
		1.1.10. Diapirism	x																
	1.2. HYDROGEOLOGICAL FEATURES	1.2.1. Groundwater flow rate			x					x			10	x				10	
		1.2.2. Characteristic hydraulic conductivity			x					x			10	x				10	
		1.2.3. Diffusion rate															x	9	
		1.2.4. Changes in existing rock permeability										x	9				x	8	
		1.2.5. Preservation of low permeability of host rock under long-term changes in tectonic stress								x			10	x				10	
		1.2.6. Preservation of low permeability under short-term dynamic stress								x			10	x				10	
		1.2.7. Water solubility of the host rock															x	7	
		1.2.8. Fossil fluid inclusions															x	8	
		1.2.9. Water solubility of the surrounding rocks			x									x					10
		1.2.10. Rock plasticity											x	8				x	8
1.2.11. Reduction of secondary porosity by closing fissures											x	7				x	7		
1.2.12. Tendency to form fluid pathways								x				9	x				9		
1.2.13. Age of groundwater								x				9	x				9		
1.2.14. Protection of aquifers	x	x	x					10	x			10	x				10		

Fig. 1. Example of steps included in application of selection criteria

2.2 Safety and Technical Requirements

The fundamental safety objective of a DGR is to ensure long-term containment and isolation of HLW and SNF, preventing harmful impacts on the biosphere. This condition is achieved through a combination of a suitable geological environment and a robust engineered barrier system.

The host rock must provide a stable, low-permeability, and geochemically favourable environment that slows radionuclide migration, protects engineered barriers, and reduces the likelihood of accidental or intentional human intrusion. Isolation is ensured primarily by repository depth and geological stability, while containment is maintained until radioactive decay significantly reduces hazard levels. The safety case demonstrates the performance of this multibarrier system, ensuring that overall safety does not rely on a single function.

Over time, degradation of engineered barriers may occur; therefore, the disposal concept must rely on complementary natural and engineered features to limit radionuclide release and transport. Key considerations include groundwater flow, geochemical conditions, and long-term geological stability, as well as avoidance of areas with valuable natural resources.

From a technical perspective, repository design and construction must preserve the integrity of the host rock and its safety functions. Excavation should minimize disturbance and the introduction of foreign materials, while allowing for adaptive design based on ongoing geological investigations. Suitable host formations include clay, crystalline rock, and salt, selected based on properties such as depth, thickness, uniformity, tectonic stability, hydrogeology, and geochemistry.

Underground Research Facilities (URFs) have crucial role in site characterization, enabling in-situ testing, validation of models, and demonstration of technologies. They support the development of the safety case and facilitate stakeholder engagement, while ensuring that their construction and operation do not compromise repository safety.

2.3 Societal requirements

Societal requirements are important to all phases of the DGR siting process, with stakeholder engagement changing in level and intensity over time.

Site selection must align with land-use plans and regulatory frameworks to minimize conflicts with existing and future activities (e.g., agriculture, resource exploitation, infrastructure, and tourism). Long-term considerations are essential, given the extended lifetime of a repository.

Transport of SNF and related materials requires optimized route planning that balances safety, environmental protection, and regulatory compliance. GIS-based spatial analysis supports route selection by integrating infrastructure, population density, environmental constraints, and risk assessment. Public opinion plays a critical role in Program success. Early assessment of societal attitudes, followed by continuous, transparent stakeholder engagement, is necessary to build trust and ensure informed participation. Key stakeholders include regulatory authorities, scientific institutions, NGOs, and local communities. Landowners are key stakeholders in the siting process, particularly in later stages. Fair, transparent land acquisition (or expropriation where necessary, community consent, and clearly defined long-term responsibilities are essential. Legal frameworks in Croatia and Slovenia guarantee property rights while allowing restrictions in the public interest with appropriate compensation. Adequate infrastructure, including power, water, transport, and communications must ensure safe and reliable repository operation.

Overall, societal acceptance, trust-building, and tangible community benefits are critical determinants of successful repository siting.

2.4 Safety assessment

The functions of each physical component of the DGR, along with their expected performance periods, will be defined and justified within the safety assessment. This assessment must also identify complementary safety functions that can compensate if a component or function

underperforms. During the RD&D stage, the safety assessment will be developed progressively, expanding and refining it in phases. At each stage, the impact of decisions, technologies, and measures on the repository's overall protective capability will be evaluated. Accordingly, the development of the safety assessment and safety case should begin early, alongside the formulation of site selection criteria.

3 TECHNOLOGIES, METHODOLOGIES AND KEY STEPS IN THE PROGRAM

3.1. GIS Technology

Geographic Information Systems (GIS) are central to site selection for SNF/HLW disposal, enabling integration, analysis, and visualization of spatial data. GIS supports multi-criteria decision analysis, combining geological, environmental, social, and regulatory factors to evaluate site suitability through deterministic or weighted models. Key functions include data integration, spatial analysis, suitability mapping, and stakeholder communication via WebGIS platforms. GIS ensures transparency, supports decision-making, and allows continuous updating throughout the RD&D Program. The GIS model development involves data integration and standardization, layered geospatial structuring, metadata documentation, spatial analysis (e.g., weighted overlay), secure data management, and software implementation.

3.2. Databases

Databases underpin GIS and MCDA by storing, managing, and enabling analysis of spatial and non-spatial data. They include geospatial, relational, geological, hydrogeological, environmental, and safety databases. Where essential datasets are incomplete, outdated, or unavailable, additional investigations and national- to local-scale studies must be undertaken prior to applying the six-phase siting methodology (2.1.; 4.), in order to ensure that all data used in the selecting process are current, validated, and fit for purpose. Core functions are data integration, quality control, spatial querying, and long-term data management. Databases must ensure security, regulatory compliance, and controlled access while supporting transparency through selective public availability.

Design principles include structured schemas, indexing, scalability, backup systems, and API (application programming interfaces)-based access. Databases also serve as document repositories and knowledge systems. Ensuring access to all relevant data especially historically fragmented or privately held datasets is critical for Program success.

3.3. Data and Knowledge Preservation

Long-term safety requires robust preservation and transfer of data and knowledge across generations. This includes comprehensive data management plans, redundant storage, standardized formats, and detailed metadata. A centralized knowledge repository should store all data, reports, and methodologies, supported by long-term governance and institutional responsibility. Education, training, and knowledge transfer mechanisms (e.g., workshops, international cooperation) are essential to maintain expertise. Transparency, regulatory documentation, and public communication must be sustained over time. Continuous updates and ethical considerations ensure adaptability and long-term trust.

3.4. Data Collection and Mapping

Data collection is conducted in phases aligned with Program development. Detailed process is addressed in the chapter "4. DGR siting process".

- **Preparatory Research:** Compilation of existing geological, hydrogeological, geophysical, and environmental data, supported by GIS analysis and initial field surveys. Outputs include preliminary identification of suitable regions.
- **Field Research:** Investigations at selected locations, including geological and hydrogeological mapping, remote sensing (LiDAR, GNSS), geophysical surveys, and exploratory drilling, with the scope progressively increasing throughout the site selection process.
- **Laboratory Research:** Analysis of samples to determine mineralogical, geochemical, and physical properties using methods such as XRD, SEM, radiometric dating etc.
- **Cabinet Research:** Integration and interpretation of all collected data to develop geological models and maps.
- **Interpretation and Reporting:** Final outputs include comprehensive geological characterization, hazard assessment, and validation of site stability and suitability.

3.5. Numerical Modelling

- **Static Geological Modelling:** Development of 3D geological models integrating borehole, geophysical, and geochemical data to represent subsurface structures and support site evaluation.
- **Groundwater Flow and Transport Modelling:** Simulation of groundwater behaviour and radionuclide transport, essential for safety assessment. Models evolve with data availability, reducing uncertainty over time. Typical workflow includes conceptual model development, numerical model simulations, calibration, validation, and predictive analysis. These models guide decision-making and prioritization in later Program stages.

3.6. Unified Implementor Organisation

Given the unique joint ownership model of the Krško NPP, a single, unified implementor for the RD&D Program is recommended. This model would mirror existing bilateral governance structures, ensuring joint decision-making while improving coordination, efficiency, and resource allocation. A unified organisation would reduce communication and operational fragmentation inherent in dual implementors, enabling clearer task distribution and streamlined management. It would also facilitate recruitment of top experts from both countries and strengthen stakeholder confidence through a cohesive approach.

Challenges include administrative harmonisation, legal alignment, staffing balance, language barriers, and potential political or public trust issues. These can be mitigated through established bilateral frameworks and coordinated regulatory oversight. Accordingly, the Fund and ARAO decided that all activities for the project will be coordinated by a dedicated project team with staff seconded from both Agencies at least until the final facility location is known.

3.7. Human Resources: Expertise, Selection and Education

3.7.1. Selection of Experts

A successful RD&D Program requires a multidisciplinary team covering technical, regulatory, environmental, safety, and social domains. Key expertise includes nuclear engineering, geosciences, environmental science, safety engineering, and public communication. Selection criteria should emphasize qualifications, relevant experience, regulatory knowledge, teamwork, and communication skills. The process must be transparent and aligned with regulatory oversight. Recruitment will primarily draw from academia, industry, and specialized institutions, supplemented by early-career professionals and, if necessary, international experts.

3.7.2. Education and Capacity Building

Education is a continuous and interdisciplinary process combining academic training, practical experience, and professional development. Core fields include engineering, geosciences, environmental studies, complemented by social sciences and communication. Training should involve international collaboration, research participation, and engagement with organizations such as the IAEA. Continuous learning is essential due to evolving technologies and regulations. Strong emphasis must be placed on interdisciplinary cooperation, stakeholder engagement, and ethical responsibility. In addition to technical experts, the implementor must include specialists in communication, economics, IT, law, and public relations.

4 DEEP GEOLOGICAL REPOSITORY SITING PROCESS

The objective of the DGR siting process is to identify two potential repository locations—one in Croatia and one in Slovenia—based on defined criteria categorized as Exclusionary and Comparative, the latter including Discretionary and Ranking criteria. The process is implemented progressively through multiple steps, combining GIS-based analysis, expert evaluation, and iterative data refinement.

4.1. Initial Survey of Territory

The first step applies exclusionary criteria to eliminate unsuitable regions across both countries using existing national datasets. These include geological hazards (e.g., active faults, seismic hazard maps), hydrogeological constraints (e.g., aquifers, groundwater protection, flooding), natural resource conflicts, and environmental or societal restrictions. A unified spatial database is developed, integrating data from institutions, agencies, and private sources. Where data gaps exist, additional research is required. The outcome is a preliminary set of suitable regions for further analysis.

4.2. Narrowing of Suitable Regions

In Step 2, additional exclusionary criteria are applied using more detailed datasets to further reduce the candidate regions. This step refines results from Step 1 and strengthens confidence in the screening process. Data limitations are addressed through targeted data acquisition and analysis. The process also supports stakeholder engagement by demonstrating a systematic and transparent approach to site selection.

4.3. Screening for Suitable Areas

Step 3 identifies smaller suitable areas (≈ 400 km²) by combining exclusionary and comparative criteria. Both safety-related (e.g., geological stability, hydrogeology) and non-safety-related factors (e.g., environmental and cultural values) are considered. This stage primarily relies on existing data, supplemented by limited field investigations where necessary. The outcome is a reduced set of candidate areas suitable for detailed evaluation.

4.4. Selection of Potential Sites

Step 4 selects up to 20 potential sites (≈ 5 km² each), approximately equally distributed between both countries. This stage involves detailed analysis using both exclusionary and comparative criteria, supported by high-quality, site-specific data. Data collection includes detailed geological, hydrogeological, geotechnical, environmental, and socio-economic investigations, as well as modelling and field studies. Both short-term analyses and long-term monitoring (e.g.,

seismicity) are required. The process ensures standardized methodologies, integration of new and existing data, and comprehensive evaluation of safety, feasibility, and societal factors.

4.5. Selection of Candidate Sites

This step identifies two candidate sites—one in Slovenia and one in Croatia—that meet all exclusion criteria and achieve the highest overall evaluation scores. Site characterization relies on both existing data (e.g., geological, hydrogeological, environmental, and socio-economic databases, maps, and studies) and newly acquired data to address gaps or uncertainties. All data must be critically assessed for reliability.

Key evaluation domains include:

- **Geological and tectonic conditions:** seismicity, fault zones, erosion, geothermal features, and long-term stability, supported by mapping, monitoring, and geophysical investigations.
- **Hydrogeological properties:** groundwater flow, permeability, solubility, and protection of aquifers, requiring detailed field measurements and modelling.
- **Surface and environmental conditions:** flood risks, meteorological hazards, geomorphology, and ecological constraints, assessed through GIS analyses and environmental data.
- **Rock characteristics:** thickness, uniformity, mechanical and geochemical properties of host rock and overburden, verified through borehole data and laboratory testing.
- **Engineering and safety factors:** slope stability, transport accessibility, infrastructure capacity, and risks from natural or human-induced hazards.
- **Socio-economic aspects:** population density, land use, infrastructure, environmental protection, and potential impacts on communities.

Where necessary, new investigations include borehole drilling, geophysical surveys, hydrogeological testing, laboratory analyses, remote sensing, and numerical modelling. The output is a comprehensive, multidisciplinary comparison of sites based on safety, feasibility, and long-term performance.

4.6. Site Confirmation

The final phase, which is not elaborated in the current Program, involves a detailed investigation and comparison of the two candidate sites to select and confirm the disposal site. Although site selection and confirmation are distinct, confirmation follows naturally if prior steps are rigorously conducted and must be approved by the regulatory authority.

This stage includes extensive, site-specific investigations such as deep exploratory drilling, coring, geophysical logging, hydrogeological testing, and long-term monitoring of groundwater and rock properties. These activities provide high-resolution data necessary to validate earlier assessments and refine the repository design to site-specific conditions.

Significant resources and time are required, as this phase relies on advanced and often invasive investigations not previously undertaken. In parallel, stakeholder engagement becomes critical; increased communication, potential incentives, and community involvement are essential to maintain support. The willingness of local communities to continue participation is a decisive factor, as withdrawal at this stage could halt and reset the entire Program.

5 PROGRAM TIMELINE AND SCENARIOS

The RD&D Program considers three timelines: a baseline case and two sensitivity cases (earlier start and extended lifetime), all of which are evaluated to assess their impact on Program feasibility, costs, and implementation. The Program is primarily based on a modified baseline scenario as “Suggested timeline scenario” (Figure 2), adapted to align with Euratom requirements

and IAEA recommendations. This adjusted timeline introduces greater flexibility, allowing for potential delays, adaptations, or even Program restart, while still enabling both countries to assess the viability of a shared disposal solution.

The baseline scenario provides sufficient time for stakeholder engagement, public education, and capacity building. This includes informing the public about ionizing radiation, radioactive waste (RW) and SNF management, and site selection processes, thereby supporting informed decision-making and acceptance of the voluntaristic approach to site selection.

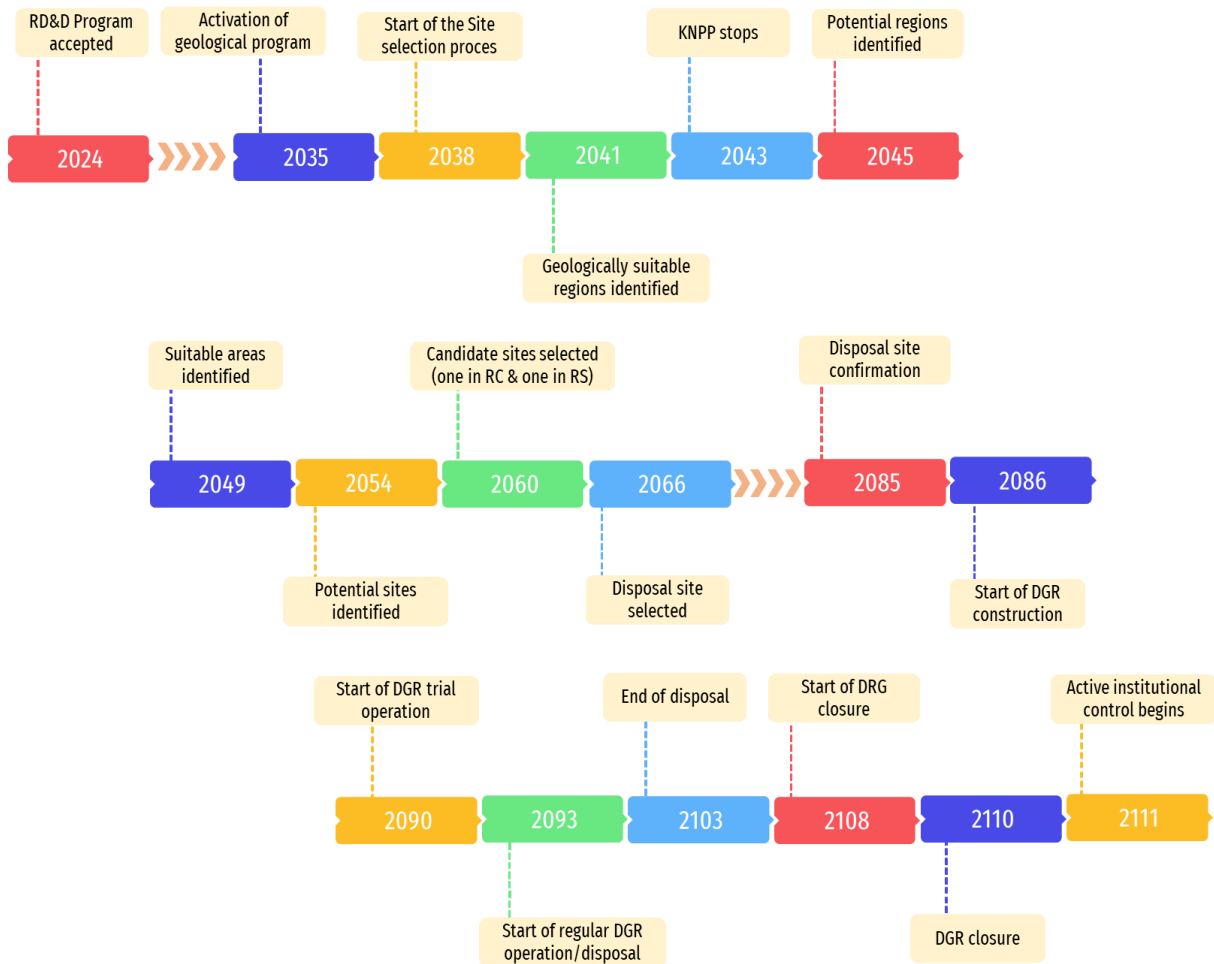


Figure 2: Simplified “Suggested scenario timeline”, with important milestones

Sensitivity analyses highlight key challenges. The earlier sensitivity case assumes a rapid Program start, including early establishment of a joint implementing organization. This introduces significant risks, such as institutional lack of capacity, regulatory gaps, limited stakeholder involvement, and overly optimistic timelines for site selection and confirmation.

Conversely, the extended lifetime sensitivity case delays key activities, raising concerns about long-term continuity. Prolonged timelines may lead to reduced stakeholder engagement, workforce attrition, loss of institutional knowledge, and risks associated with deferred responsibility – contrary to the widely accepted principle that radioactive waste and SNF management should not be postponed to future generations. Overall, the modified baseline scenario represents a balanced approach, accommodating technical, institutional, and societal constraints. Early initiation of organizational development and stakeholder engagement is essential to ensure Program credibility, transparency, and long-term success. A detailed breakdown of the proposed timeline and associated activities is provided in Larva et al. (2024).

6 RD&D COST ESTIMATES

For this RD&D Program, the costs have been estimated using a combination of Engineering Built Up, Analogous and Parametric estimating methods. Engineering Built Up Estimating was used to create a Work Breakdown Structure (WBS), breaking down each stage of the Program implementation process into specific steps with definable costs. Within these individual steps, an Analogous Estimating was then used for cost items common to similar programs (in this case, the cost of a program applied in the Czech Republic). In some cases, where the calculations were more complex (personal costs), Parametric (top-down) Estimating was used, using the long-term salary development and its trend with the projection of the prediction into the future. The specific average salary data are based on current Croatian salary ranges and have been further adjusted for the extent of contingencies.

The costs have been divided into three main groups within the WBS.

- The implementing organization costs
- The Stakeholder involvement costs
- The Costs for the particular technical and geological outsourced work.

For the financial calculation, the individual cost items were further defined as: Personal costs, Leases, Services (Time dependent and Time independent; Dealt with by the implementor itself / Outsourced), Investments, Value added tax (VAT), Contingencies and Risks.

The base case scenario, starting in 2026 and aiming to identify two candidate sites by 2060, estimates total costs at EUR 139.816 million (without VAT). This includes EUR 2.983 million for the preparatory phase (2025–2032) that involves both countries' organizations (ARAO in Slovenia and the Fund in Croatia) until a unified implementor is established post-2032.

7 PREOPERATIVE MONITORING

The primary objective of preoperative monitoring is to support informed decision-making throughout repository development by providing reliable and comprehensive data. Key functions include informing stepwise Program implementation, improving understanding of system behaviour, supporting safety case development and model validation, demonstrating protection of human health and the environment, and fulfilling regulatory and safeguards requirements.

A central task is the establishment of baseline conditions, which serve as a reference for distinguishing repository-induced changes from natural variability and other anthropogenic influences. These baseline datasets are essential for validating site-specific models, refining repository design, and supporting safety assessments. Comparisons between baseline and later monitoring data enable evaluation of environmental impacts and demonstration of regulatory compliance.

Baseline conditions must be comprehensive, well-documented, and monitored over sufficiently long periods to capture natural variability (seasonal to long-term trends). Monitoring should begin as early as possible, ideally during site selection, and continue until key trends are reliably established.

- **Ambient Baseline:** Monitoring should include external factors that may influence site conditions, such as traffic, pollution sources, and infrastructure (roads, railways, power lines). These observations are required throughout all phases of the DGR Program.
- **Ecosystems:** Baseline ecosystem characterisation includes forestry, agriculture, water balance, climate, soil, flora, fauna, surface water, and groundwater conditions. In addition, background levels of natural radioactivity and anthropogenic radionuclides must be established across environmental compartments.
- **Geology:** Although most geological investigations are conducted separately, monitoring should include geothermal conditions (heat flow, temperature distribution) and seismic activity (e.g., magnitude, hypocentre), both relevant for repository performance.

- **Hydrogeology:** Hydrogeological monitoring provides data on groundwater systems, including hydraulic heads, recharge, flow conditions, temperature, and density. Surface hydrology (streamflow and lake levels) should also be monitored. These data are essential for developing and refining groundwater models.
- **Hydrogeochemistry:** Hydrogeochemical monitoring aims to characterise groundwater composition and evolution. Key parameters include pH, redox potential, major ions, trace elements, gases, isotopes, and microbial content. Long-term, repeated measurements are required to support model calibration and safety assessment.

8 COMMUNICATION SUPPORT AND STAKEHOLDER ENGAGEMENT

The stakeholder map (Figure 3) presents an initial overview of key stakeholders and stakeholder groups in Slovenia and Croatia relevant to the project communication process. At this stage, the map reflects stakeholder categories at a general level, focusing on groups that may influence or be affected by project implementation. As the project progresses, this mapping should be progressively refined, transitioning from group-level categorisation toward identification of specific organisations and individuals.



Figure 3: Stakeholder map

Stakeholder management follows a differentiated engagement approach based on levels of interest and influence. Stakeholders with low interest and low influence require only monitoring. Those with high interest but limited influence should be kept well informed, while stakeholders with strong influence but low interest should be actively managed and kept satisfied through targeted communication. Stakeholders with both high interest and high influence require continuous, structured engagement, with close attention to expectations and concerns.

Effective communication is a central component of HLW and SNF disposal programs, supported by three interconnected pillars of communication strategy (Figure 4). Successful implementation requires a dedicated, multidisciplinary team with competencies in public relations,

social sciences, psychology, project management, and stakeholder analysis. This team should also include expertise in public opinion research and Program evaluation, either internally or through external consultancy.

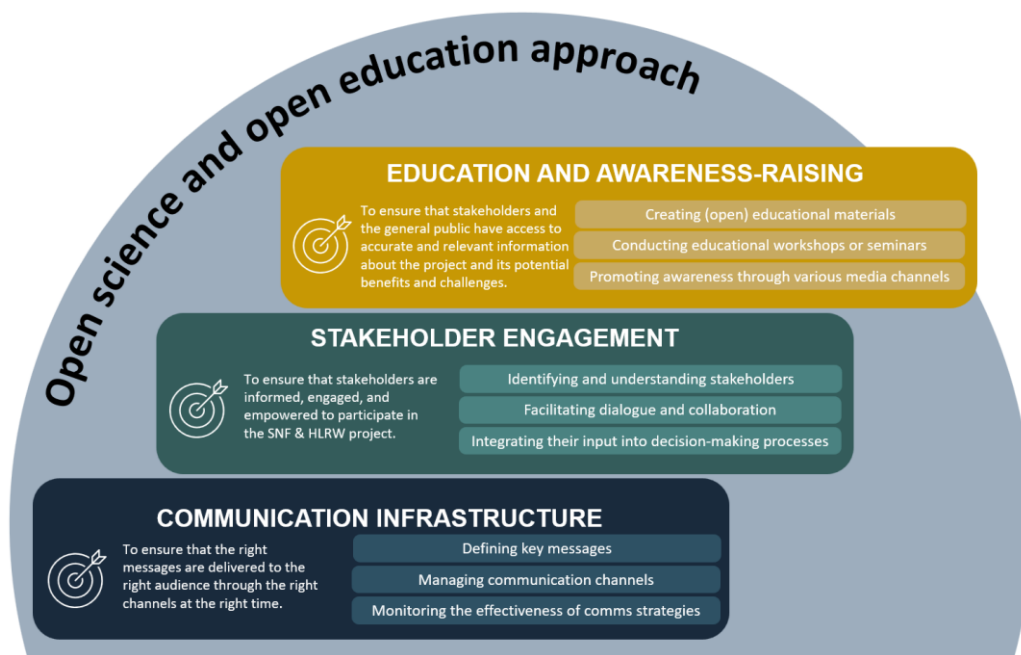


Figure 4: The three pillars of communication strategy

Special attention must be given to the role of non-governmental organisations (NGOs), which can significantly influence public perception and information dissemination. Early and proactive engagement is essential to ensure constructive involvement and alignment with the overarching goal of improving safety and environmental protection.

Given the cross-border nature of the Program, communication must address differing perceptions and attitudes in Slovenia and Croatia. Misconceptions regarding ownership and responsibility for the KNPP and associated waste streams must be addressed through clear, consistent messaging. Key messages should emphasise shared ownership, joint responsibility, mutual benefit, and transparent implementation based on best available technology and expertise. The establishment of a unified implementor located near the future repository site is intended to reinforce the joint nature of the Program and strengthen public trust. Fragmentation into separate implementing bodies may negatively affect coordination, efficiency, and stakeholder confidence.

Finally, a dedicated Stakeholder Engagement Program should be developed as a separate document. This Program will define detailed procedures, roles, timelines, and evaluation methods for stakeholder engagement activities and is already considered within the project cost and schedule framework.

9 CONCLUSIONS

This RD&D Program is challenging, particularly since the SNF and HLW to be disposed of in a single mined DGR are shared equally between two countries, and because the disposal site must be selected based on studies of the relatively small territories of both countries; consequently, there is a relatively limited area within which an appropriate location for the DGR must be selected. Since the RD&D Program is the same for both countries, it is crucial to consider the harmonization of the regulatory documents of both countries. The "volunteering approach" principle has to be a part of the RW/SNF management policy and future regulatory framework. The level of stakeholder involvement in site selection will be determined by the regulatory body (or bodies), and the implementor(s). However, stakeholders must be involved in the development and formalisation of

the criteria for DGR site selection. Moreover, stakeholders must be included in an intensive information and education process. Based on lessons learned from similar programs, the ability of implementers to engage in stakeholder dialogue and to adapt to an evolving social context during the site selection process appears to be the most critical criterion for successful Program implementation.

The Program described in this paper is the first joint RD&D Program for the disposal of SNF from the Krško NPP, and it will evolve over time through an iterative process. It will need to be adjusted in response to changes in timeline, costs, approaches, technologies, and other relevant factors.

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