Deep Borehole Disposal As An Alternative Disposal Option for Spent Fuel

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ABSTRACT

Many countries are developing a geological disposal project to dispose of their high-level radioactive waste (HLW) as well as spent nuclear fuel (SF) when considered as waste. The most widely selected option is the deep geological repository (DGR) concept, a mining repository located underground in a geological layer, in which conditioned waste is disposed of.

A potentially practicable, but less developed alternative to mined repositories that has received increased attention in recent years, is deep borehole disposal (DBD), involving disposal of highly active wastes in boreholes drilled to depths of a few kilometres for power programs or countries that do not use nuclear power but have small quantities of radioactive waste (RW) from other nuclear applications (such as research reactors) that also require geological disposal.

In 2021, ARAO investigated whether a DBD could be used for disposal of SF from Slovenia's Triga Mark II research reactor operated by Jožef Stefan Institute. DBD for SF from Krško NPP was first analysed in 2022 through joint ERDO Association collaborative project. The project assessed the strategic potential of DBD for several European countries, based on their existing and projected national waste inventories. DBD option of Krško NPP SF has been in 2023 additionally and more extensively analysed as part of the preparation of the Fourth Revision of the Krško NPP Radioactive Waste and Spent Fuel Disposal Program.

This paper provides basic design information and cost estimates about the DBD for SF from Triga Mark II Research Reactor and SF from Krško NPP as well as conclusions and planned activities to further explore this disposal option.

1 INTRODUCTION

Geological disposal of RW or SF refers to the disposal of waste in a Deep Geological Repository (DGR). A DGR is a facility implemented for the "disposal of solid radioactive waste" that is "located underground in a stable geological formation so as to provide long term containment of the waste and isolation of the waste from the accessible biosphere" [1]. Another disposal option can be achieved through disposal in a Deep Borehole Facility (DBF). A DBF achieves the same function but using "specially engineered and purpose drilled boreholes" which "offers the prospect of economic disposal on a small scale while, at the same time, meeting all the safety requirements" [2].

A DBF would emplace wastes at considerable depth in a borehole some tens of centimetres wide in a suitable geological environment. The waste is typically placed in canisters or containers, which are then lowered into the borehole to a predetermined depth within a stable geological formation. The borehole would then be closed and sealed over many hundreds of metres of its length, perhaps up to several kilometres of its length, back to the surface [3]. During the last decade, advances in drilling technology and simultaneous lack of progress for some disposal programs have reinvigorated research into borehole disposal.

There is not a unique concept for a DBF, and many designs have been considered over several decades of development and evaluation. The Figure 1 illustrates the rationale behind DBD concept, the role of the engineered and natural barriers in providing safety and gives a spectrum of potential depths and designs for the DBF [3].

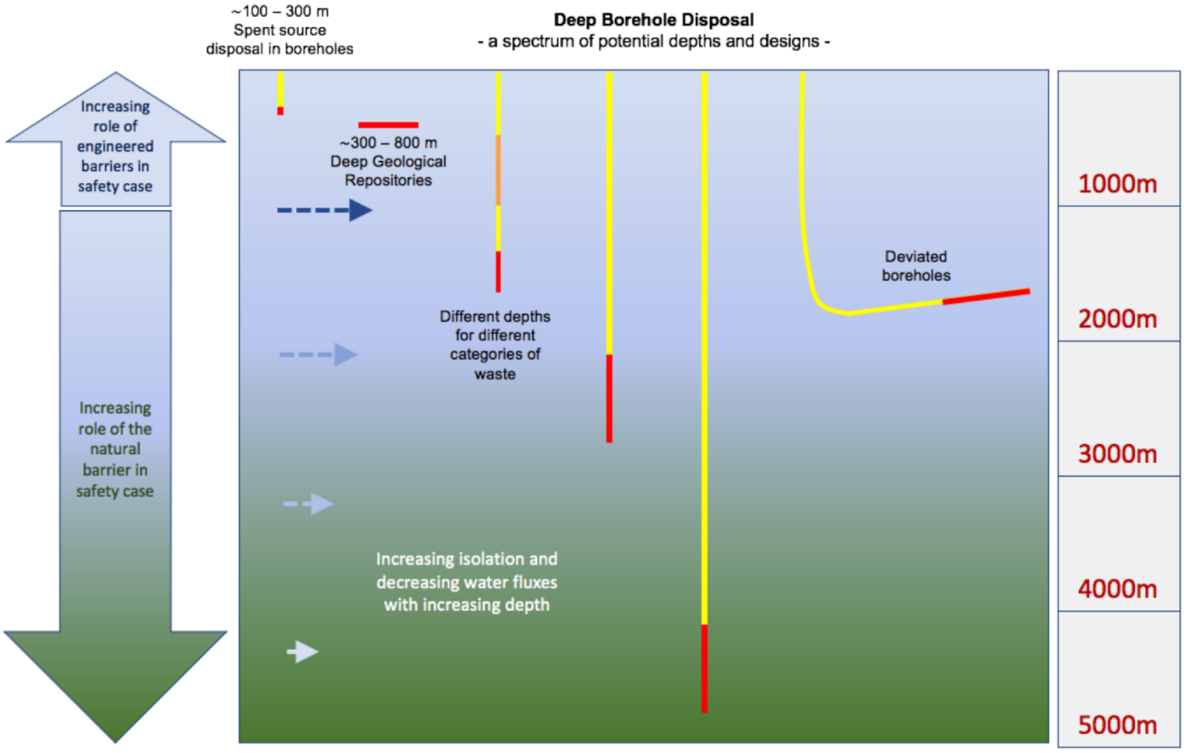

Figure 1: DBD concept explained for different depths and variants [3].

The greater depth of DBF enhances isolation of the waste but constrains the dimensions of waste packages compared to what can be emplaced in a DGR. As depth and isolation increase there is a reduction in the need for engineered barriers to provide containment, as indicated on the left-hand side of the Figure 1. DBD is primarily being considered for relatively small quantities of radioactive waste and may be particularly suited to those countries with smaller SF inventories or other hazardous materials.

In line with requirements of the Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste [4], in 2023, Slovenia adopted the Third national programme: Resolution on the National Programme for Managing RW and SF for period 2023-2032 (ReNPROIG23-32) [5].

In Chapter 4 of the ReNPROIG23-32, strategies are envisaged for RW and SF management during the operation of nuclear and radiation facilities with planned measures to achieve the objectives of the presented strategies. Under Strategy 5, for SF and high-level waste (HLW) storage and disposal, it is required that ARAO shall periodically check the comparison of the disposal concepts, costs and administrative requirements for the preparations for construction, construction and the disposal of HLW and SF in a national, regional or multinational repository. In addition to the basic concept of disposal in hard rock, the option should be explored of disposing of HLW and SF in deep geological boreholes or employing other suitable options.

2 ARAO ACTIVITIES IN EXPLORING DEEP BOREHOLE DISPOSAL

2.1 An assessment of the suitability and costs of disposing Slovenia's TRIGA II research reactor fuel

In December 2021, Preliminary feasibility study on disposal of TRIGA II research reactor SF using a Deep Isolation repository was prepared [6].

The purpose of this study was to provide an initial assessment of DBD and to carry out an assessment of the suitability and costs for disposal of Slovenia's TRIGA II research reactor fuel. The project has reviewed the available data on the TRIGA II research reactor SF, and by 2043, the point at which the research reactor will cease operations, there will be a total inventory of 84 TRIGA spent fuel items (both fuel elements and fuel followers) ready for disposal. The TRIGA SF element is 72.1 cm long and has a diameter of 3.7 cm. In total, 71 standard SF elements with 12% uranium content need to be disposed. In addition to that, 9 fresh fuel elements, 3 spent fuel followers for control rods and 1 fresh fuel follower for control rod will be disposed.

In this preliminary study, detailed screening of Slovenian communities against the geological site screening criteria have not been undertaken. Geological requirements were identified through existing high-level data review for palaeohydrological, geothermal heat flux and volcanism, climate change and seismicity factors. Preliminary conclusion is that all areas of Slovenia are potentially suitable for DBD of nuclear waste. These factors will need to be further addressed during future detailed site characterization work and factored into the design and planning of borehole construction at any selected site [6].

2.1.1 Disposal Options Analysed

Baseline disposal architecture (Option 1) was based on a vertical borehole drilled to a safe depth of 1.5 kilometres (assumed for generic costing purposes), with a very short vertical disposal section and using 1 standard Deep Isolation canister with 34 cm diameter [6].

In addition, other potential scenarios were explored:

- Option 2: disposing the same standard single Deep Isolation canister, not within a DBF dedicated only to TRIGA II waste but as a marginal addition to a larger DBF that is also disposing the spent fuel from the Krško nuclear power plant[1].
- Option 3: developing a bespoke canister specially for the TRIGA II fuel elements, enabling use of a significantly lower diameter (and hence lower cost) borehole.

[1] A repository for Krško SF with NPP operation until 2043, is expected to contain 11 boreholes, with 2,282 canisters of waste, and with boreholes drilled in parallel and bending to be horizontal or sub-horizontal. These generic assumptions may change depending on the geology of a specific selected site.

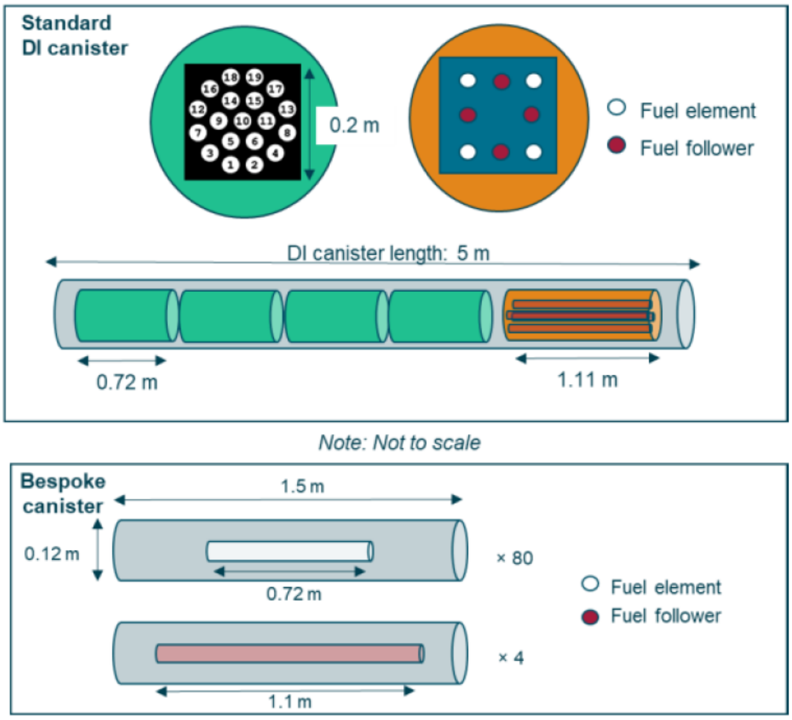

Figure 2: Summary of the options analysed during the study.

2.1.2 Cost estimates

The costs of planning, constructing and operating the DBF on-site facilities and functions contained were analysed for each of the three options we have considered. The cost estimates were prepared for undiscounted lifetime costs, covering all activities needed to plan, site, construct, operate and close the repository to provide support for a possible decision to further explore the DBD option for TRIGA II fuel. Out of scope for this assessment were the costs of off-site storage, encapsulation in disposal canisters and transportation to the DBF, and any payments to the communities and/or landowners in respect of e.g. compensation for limited land use [6].

Based on Figure 3, option 2 (adding the TRIGA fuel to an existing repository for Krško SF) is by far the most cost-effective option due to sharing of the wider fixed costs of that repository that should properly be accounted for by the TRIGA fuel. However, this is not an option that the organisation responsible for disposal can rely on, because it is dependent on national policy and strategy decisions.

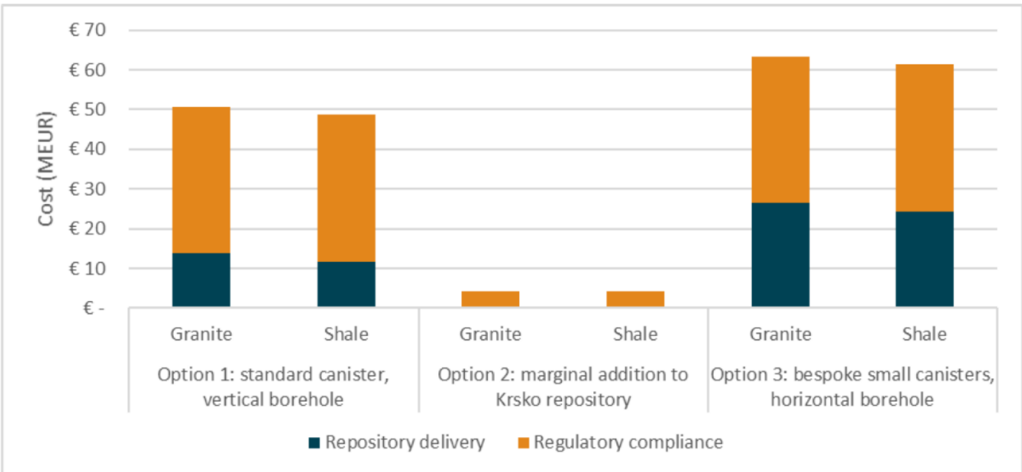

Figure 3: Overview of costed scenarios for DBD of TRIGA II SF [6].

Looking at the two stand-alone options for TRIGA II disposal, then option 3 is around a quarter more expensive than option 1 but with potential delivery benefits to weigh against each other during the design process to evaluate them accordingly. It is also worth highlighting that Options 1 and 3 both offer the advantage that they would enable the disposal of TRIGA II SF within just one year of the research reactor's planned closure in 2043 and thus avoiding the need for costly investment in temporary storage for the TRIGA II fuel pending final disposal in a national DGR planned several decades later [6].

2.1.3 Preliminary conclusions and recommendations for further work

Based on this preliminary assessment, initial conclusion is that TRIGA II SF is suitable for DBD, and potentially suitable disposal areas exists in Slovenia. All of the TRIGA SF could be disposed of within a micro DBF consisting of a single borehole at a reactor or other site and thus avoiding the need for planned expenditure on temporary storage. The optimum approach, however, would involve not such a stand-alone micro DBF but instead disposing of the TRIGA II waste in a larger DBF capable also of disposing SF from the Krško nuclear power plant.

Further work is needed to refine this preliminary analysis:

- Development of a Generic Safety Case for DBD: It will be essential to document a Generic Safety Case tailored specifically to Slovenian geology with quantitative evaluation of the geologic, hydrologic, rock mechanical and geochemical conditions in potential regions and to model the long-term environmental performance of the DBF.
- More detailed analysis to refine preliminary cost estimates: Analysis of regulatory and licensing requirements, to clarify retrievability requirements and post-closure monitoring periods, TRIGA II inventory refinement – including optimization of canister size and number.
- A full strategic appraisal of the costs of borehole disposal for Krško NPP SF and development of an overarching strategy and roadmap for combined disposal of both the Krško and TRIGA II SF inventory.
- International collaboration in relation to DBF demonstration and cost sharing.

2.2 An assessment of borehole disposal as a permanent solution for ERDO Association national inventories of RW

In 2022, under the umbrella of Joint ERDO Association project, a report was produced that considers whether DBD might be an alternative disposal option suitable for inventories of RW from Austria, Croatia, Denmark, The Netherlands, Norway, and Slovenia [7].

A reference design for DBF has been selected with the reference borehole 3500 m deep and 0.775 m wide. The reference canister has an outer diameter of 0.6 m, which leaves room for casing within the borehole. The canister exterior consists of 80 mm of austenitic or duplex steel, which gives sufficient mechanical strength to withstand the pressures at the bottom of the borehole and enough chemical stability to remain intact for at least 1000 years [7] and ensures compliance with the IAEA Specific Safety Requirements [8].

The ambition has been that one canister design should be able to accommodate as many of the waste forms from the different countries as possible, but at least with three different waste forms:

- reprocessing waste (which is part of the Dutch waste inventory),
- a SF assemblies from Krško NPP,
- primary packages in which Danish spent-fuel residues are contained.

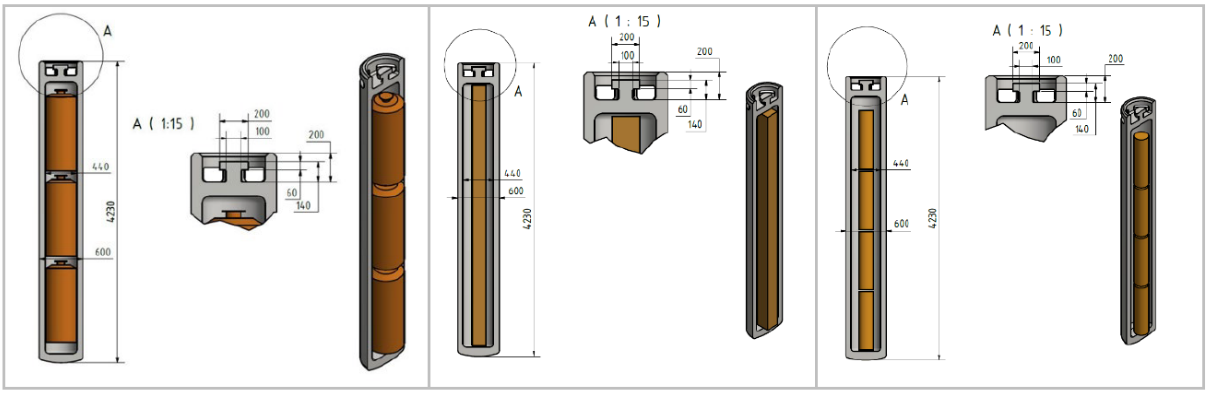

Figure 4: Canister with reprocessing waste (left), SNF (Krško NPP, middle), and Danish waste (right).

2.2.1 SF inventory from Krško NPP

Croatia and Slovenia share ownership and responsibility for the nuclear powerplant in Krško, Slovenia. It has been in operation since 1983 and is expected to remain in operation until 2043, by which time 2282 assemblies of SF will have been generated.

Slovenia is in the process of implementing a near-surface repository for LILW at Vrbina, in the Municipality of Krško. This is intended to receive all radioactive waste other than SF and other HLW, including half of the low- and intermediate level waste (LILW) from operation and decommissioning of Krško NPP. Slovenian LILW disposal was therefore not discussed further in the report [7].

2.2.2 Cost estimates

The costs of a DBF depend on the design, which in turn depends on the waste form, the size of the waste inventory, the geological conditions, and the safety requirements. All these factors could vary from country to country.

Deep borehole variations were analysed for three generic designs with different depths and different emplacement zones and corresponding cost estimates were produced. In addition to the described conceptual costs, uncertainties in construction costs per borehole and operational costs per canister were assessed using a flat probability distribution range based on a literature review and dialogue with the industry [7].

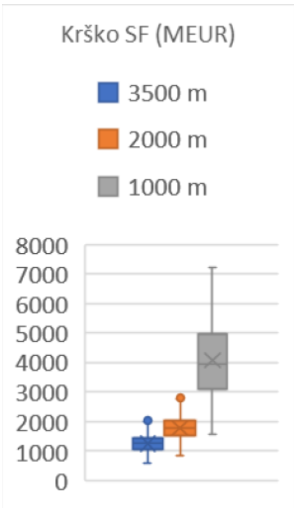

Figure 5: Cost estimates for disposing of the Krško NPP SF inventory in boreholes of different depths presented in million EUR.

In case of Krško NPP SF, disposal in reference depth of 3500 m is the most cost efficient due to economies of scale with the largest length of emplacement zone per borehole and smaller number of boreholes. It has been estimated that the cost of a single multinational DBF for the combined inventory from Croatia, Slovenia, Denmark, The Netherlands and Norway would cost between 56 and 65 % less than a mined DGR for the suitable waste inventory. It was also found that a multinational DBF would cost about two thirds of separate DBFs in the respective countries [7].

2.2.3 Conclusions and future work

DBD is a technologically feasible and potentially cost-efficient solution for HLW, long-lived intermediate level waste and SF from Croatia, Slovenia, Denmark, The Netherlands, and Norway. A multinational DBF is likely to be more cost-effective than separate national repositories.

A lot of work has been done on DBD at the conceptual and generic level. To secure progress of this disposal option, DBF should become part of a national or multinational disposal program in the same way as mined repositories have been developed in several countries over several decades (such as in Finland, Sweden, Canada, France and others). Additionally, there is a strong need for full-scale demonstration of site characterisation, drilling, waste emplacement, and borehole sealing that is properly supported by the safety case developed in line with best international guidelines and practice. This will enhance confidence in DBFs and identify priorities for further development and demonstration work.

2.3 Costing Study for Disposal of SF and HLW from the Krško NPP in Deep Boreholes

Preparation of joint Krško NPP Radioactive Waste and Spent Nuclear Fuel Disposal Program (Disposal Program) and joint Krško NPP Decommissioning Program and regular revisions of both programs is stipulated in the Agreement between the Government of the Republic of Croatia and the Government of the Republic of Slovenia on the Regulation of the Status and Other Legal Relations Regarding the Investment, Exploitation and Decommissioning of the Krško NPP (Bilateral Agreement). Intergovernmental Commission, established for monitoring the implementation of the Bilateral Agreement, at its 16th meeting, in April 2022, approved the Terms of Reference for the preparation of the 4th revision of the Disposal Program.

For this purpose, for a comprehensive assessment of costs and further decision-making on the SF disposal strategy, it is necessary to analyse the possibility of SF disposal in deep geological boreholes as an alternative disposal concept, in addition to disposal in a DGR.

In this regard, ARAO and Fund for Financing the Decommissioning of the Krško Nuclear Power Plant and the Disposal of Krško NPP Radioactive Waste and Spent Nuclear Fuel from Croatia (Fund NEK) in June 2023, commissioned 2 studies to evaluate the cost for HLW and SF disposal in hard rock and sedimentary geological formations, and as an alternative, DBD for the Krško SF.

Deep borehole disposal will be analysed in a range of scenarios:

- Timescale: The study will evaluate a Base Case (BC) scenario in which the Krško NPP ceases operations in 2043 and an Extended Lifetime Sensitivity Case (ELSC) in which the power plant continues operations until 2063. In both cases, current policy is that no field-based activities to identify and investigate potential sites for a disposal facility will begin until 2050. Additionally, compressed timetable for an Earliest Possible Disposal (EPD) scenario (including an estimated RD&D budget associated with this option) will be prepared.
- Geology: The study will look at how costs vary between disposal in sedimentary rock and disposal in crystalline rock.

- Location: The study will compare disposal costs at Krško with disposal at a ‘generic’ Slovenian/Croatian location.
- Borehole architecture: The study will compare disposal costs of vertical and horizontal disposal options.

All SF inventory (Table 1) will be disposed in several deep boreholes at a single location and the SF encapsulation plant will be located at the DBF.

Table 1: Expected number of SF elements for BC and ELSC scenarios.

Case/scenario	BC	ELSC
Number of fuel elements	2282	3182

Cost sensitivity analyses to various depths and numbers of boreholes will also be prepared. The study needs to be finalized by February 2024 and will provide information for making decisions for further exploring DBD.

3 CONCLUSION, CHALLENGES AND OPPORTUNITIES

Deep borehole disposal is a technologically feasible and potentially cost-efficient solution for HLW, long-lived intermediate level waste and SF from Krško NPP and Triga II research reactor. But still in wider international community, a lot needs to be done in resolving siting issues, geological data acquisition, developing proper safety case, …, and mostly to implement demonstration of SF canister emplacement, its potential retrieval if required and sealing of boreholes.

Currently, due to ReNPROIG23-32 defined key milestones and especially due to construction of LILW repository only generic locations and parameters will be used for planning and costing purposes.

ARAO will in line with ReNPROIG23-32, alone and together with Fund NEK or partners from ERDO Association, continue to develop DBD and will monitor its progress in other countries. ARAO is interested in wider international collaboration on deep borehole option and will therefore be part of EURATOM EURAD-2 project, work package ASTRA, that will address DBD technological readiness level and associated challenges. ARAO will probably join recently announced IAEA coordinated research project on DBD [9] with objective to provide a comprehensive suite of assessments at the strategic and programmatic level to help countries make an informed decision on DBD option.

Results of ongoing Costing study for disposal of SF and HLW from the Krško NPP in deep boreholes will be used to support future decisions and to inform national stakeholders how to progress and implement this option. Additionally, Triga II SF disposal in deep boreholes need to be further analysed with adding more details to the concept and focusing more on development of a Generic Safety Case and preparing roadmap for combined disposal of both the Krško and TRIGA II SF inventory.

REFERENCES

[1] https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1483_web.pdf

[2] https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1418_web.pdf

[3] N. Chapman, Understanding Deep Borehole Disposal Technology in the context of Spent Fuel and High-Level Radioactive Waste Disposal: History, Status, Opportunities and Challenges, IFNEC webinar, November 2020.

[4] Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, OJ L 199, 2.8.2011.

[5] Resolution on the National Programme for Managing Radioactive Waste and Spent Nuclear Fuel 2023-2032 (ReNPROIG23-32), Official Gazette of RS, Nr. 14/23.

[6] Preliminary feasibility study on disposal of Triga RR SF using a Deep Isolation repository, Deep Isolation EMEA, December 2021.

[7] Boreholes as a permanent solution for national inventories of RW, ERDO Association, May 2022.

[8] “Disposal of Radioactive Waste”, IAEA Specific Safety Requirements No. SSR-5, IAEA, 2011.

[9] https://www.iaea.org/newscenter/news/new-crp-enhancing-global-knowledge-on-deep-borehole-disposal-for-nuclear-waste-t22003