Deep borehole disposal for TRIGA II fuel at and away from Krško basin:

Cost Study

FINAL REPORT

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Contents

Figures

Tables

Executive summary

This report updates findings from Deep Isolation's 2021 study on testing, research, isotopes, general atomics (TRIGA) II spent nuclear fuel (SNF) disposal [1], in the light of its more detailed 2024 study on disposal of SNF from the Krško nuclear power plant (NPP) [2]. The update enables direct comparison of the costs of TRIGA II and Krško SNF, by updating our 2021 TRIGA II analysis to use the same more detailed and EURAD-aligned work breakdown structure that was deployed in the 2024 Krško study, and by updating TRIGA II cost estimates into 2023 Euros as per the 2024 study.

This study affirms the following:

- **Co-located disposal of the two SNF inventories is by far the most cost-effective option**:
  - When added to a borehole repository sized to manage the much larger Krško inventory, the TRIGA II SNF only adds **€1.5M** (excluding contingencies and value-added tax (VAT)[1]). This added cost is identical for a base case schedule, an earliest possible disposal scenario, and an extended lifetime sensitivity case. This represents an additional 0.25% on top of the base case scenario for disposal of the Krško spent fuel in the 2024 study[2].
  - By comparison, a standalone TRIGA II SNF repository would cost **€65.6M** (excluding contingencies and VAT[3]). The relatively higher cost is due to many cost areas having fixed or semi-fixed costs not fully correlated with the volume of inventory being disposed of in a repository.

- **No significant programmatic impacts**: In either scenario (co-located disposal or standalone TRIGA II repository), the safety, compatibility, and schedule assumptions from the 2024 Krško study are not noticeably affected. Adding a single canister of TRIGA II SNF may add a day to a Krško disposal case, whereas a standalone TRIGA II SNF repository could be operated and closed slightly ahead of the Krško earliest possible disposal scenario. Both timelines are significantly faster than mined repository timelines.

- **Differences from 2021 (after inflation)**:
  - The €1.5M incremental cost of adding TRIGA II SNF to a Krško repository is about 70% cheaper than determined in 2021. This is largely due to the fact that the 2021 study took a preliminary and deliberately cautious approach to estimating siting and licencing costs on a top-down basis. These estimates have now been updated using the more detailed and bottom-up analysis of such costs undertaken for the 2024 Krško cost study.
  - The standalone TRIGA repository, however, is 16% more expensive than determined in 2021 (excluding contingencies and VAT). This is primarily due to costs such as community compensation being considered out of scope in 2021.
  - Both more recent estimates therefore have greater granularity and credibility.

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[1] Applying the same methodology from the Krško study, adding a contingency budget and Slovenian VAT would add €0.3M to the co-located disposal case, resulting in a total budget addition of €1.8M.

[2] Note that the additional TRIGA canister represents 0.04% of Krško volume, so cost increase is significantly larger than inventory increase.

[3] For a standalone TRIGA repository, contingency budget and Slovenian VAT add €32.6M, resulting in a total budget of €98.2M. The cost increase is greater for the standalone TRIGA repository because of the higher base costs in categories incurring both significant contingency costs and VAT such as drilling and canisters, whereas these additions are minimal in the TRIGA addition scenarios.

1. Introduction

This draft report has been prepared by Deep Isolation as an interim deliverable from our study into costs of delivering deep borehole disposal for the spent nuclear fuel (SNF) from the testing, research, isotopes, general atomics (TRIGA) II reactor at the Jožef Stefan Institute in Ljubljana, Slovenia. Deep Isolation will issue a final version of this report following incorporation of additional client feedback in November 2024.

1.1. Background

This study serves as an addendum to Deep Isolation's 2024 study on deep borehole disposal of SNF from the Krško nuclear power plant (NPP) in Slovenia [1] and provides an update to Deep Isolation's 2021 study on borehole disposal of TRIGA II SNF [2].

1.2. Scope and structure of this report

The study aims to inform understanding of how deep borehole costs will vary in two scenarios:

a) **Co-located disposal:** the addition of SNF from the TRIGA II reactor into a Krško SNF repository, as an incremental addition to the Krško inventory

b) **A standalone repository** developed solely for use with the TRIGA SNF

Scenario a) is assessed in Section 2 of this report. Whereas the 2024 Krško cost study reviewed nine potential scenarios (as shown in Table 1 below), this report will limit focus to the three scenarios in which the Krško NPP inventory is disposed at the Krško basin (as shown in Table 2 below).

Table 1: Five scenarios for cost analysis in our 2024 Krško cost study

Geology/Location/Architecture	Timeline		
	Base Case	Extended Life Sensitivity Case	Earliest Possible Disposal Case
a) Horizontal repository in sedimentary rock in a generic Slovenian location	●	○	○
b) Vertical repository in basement rock in the same generic Slovenian location	●	○	○
c) Horizontal repository in sedimentary rock in Krško basin	●	●	●

Key: ● Full costed scenario using EURAD[4] Work breakdown Structure ○ Top-level analysis of key cost differences

Table 2: Three scenarios for cost analysis in Section 2 of this report

Geology/Location/Architecture	Timeline		
	Base Case	Extended Life Sensitivity Case	Earliest Possible Disposal Case
Horizontal repository in sedimentary rock in Krško basin	●	●	●

Key: ● Full costed scenario using EURAD Work breakdown Structure

[4] EURAD: European Joint Programme on Radioactive Waste Management

The three timelines shown in the Table 2 column headings are:

- **Base Case (BC):** In which the Krško NPP ceases operations and commences decommissioning in 2043, and the timeline for siting and constructing a DBD repository largely mirrors that currently assumed for a mined geologic disposal facility.
- **Extended Life Sensitivity Case (ELSC):** In which the Krško NPP continues operating until 2063.
- **Earliest Possible Disposal (EPD):** Deep Isolation's advice on a more compressed timetable for disposal, linked to 2043 closure of the Krško NPP as in the Base Case.

Section 3 of this report then evaluates the cost of a standalone repository for the TRIGA II SNF inventory. These costs are compared against base case b) from Table 1 above (vertical borehole offsite) to determine how various costs scale with inventory size.

The cost subtotals calculated in Sections 2 and 3 are then incorporated into a sensitivity analysis for contingency budget and value-added tax (VAT) determination, at Section 4. Results and commentary are then summarized in conclusions in Section 5. This includes comparisons between Sections 2 and 3 findings versus results from Deep Isolation's 2021 TRIGA study which did not utilize the current EURAD-aligned work breakdown structure.

2. TRIGA II addition to Krško SNF inventory

2.1. Foundational assumptions

Prior to reviewing subsequent cost analyses, please note the following key assumptions taken from the 2024 Krško study [1], the 2021 TRIGA II study [2], and reasoning agreed upon by the client (ARAO) in an October 2024 workshop with Deep Isolation:

- The TRIGA II inventory (84 small SNF items) can be packaged in a single drillhole canister (DHC) geometrically and economically similar to if not identical to the 2282 DHCs required for the Krško NPP SNF inventory, meaning that **no change in borehole dimensions** is needed to accommodate TRIGA SNF.
- The planned 2043 shutdown of the TRIGA II reactor would prompt **no delays or schedule-related cost additions** beyond the marginal operational increase for emplacement of its one DHC. This assertion is made for all cases, including EPD.
- The DHC containing TRIGA II SNF is assumed to be **bounded from a thermal and radiological standpoint** by a DHC containing Krško SNF, meaning **no additional engineering on account of safety**.

2.2. Summary

Section 2.3 below compares the Krško SNF Base Case costs in a horizontal disposal in sedimentary host rocks in the Krško basin with the additional cost to scope in the TRIGA II SNF inventory. These costs (expressed in 2023 Euros for consistency with the Krško study) calculate the actual delivery cost of repository planning, construction, operation, closure, and post-closure institutional control. Other related costs – such as value-added tax (VAT) and contingencies – are then shown additionally in Section 4.

The overall conclusion is that adding TRIGA II SNF to a repository in the Krško basin yields an insignificant increase in cost. The areas where costs do increase are primarily in stakeholder engagement due to a transport route and encapsulation facility CapEx and O&M to encapsulate the TRIGA II SNF. Most other cost areas are unchanged or insignificantly changed. Total lifetime cost for siting, construction, operation, and closure of the repository in sedimentary host rocks in the Krško basin with the addition of TRIGA II SNF is €580 million (a €1.5 million or 0.3% cost increase).

The cost increase is identical for all other co-located Krško basin scenarios, resulting in these updated costs:

- €746 million in the Extended Life Sensitivity Case (a €1.5 million or 0.2% cost increase).
- €496 million in the Earliest Possible Disposal scenario (a €1.5 million or 0.3% cost increase).

Due to the identical and insignificant nature of cost increases for these two scenarios, only the base case will be elaborated upon in detail in the remainder of this section.

Lastly, it is worth noting that €1.5 million estimate for adding the TRIGA SNF inventory to a Krško SNF repository is about 70% less than the €4.9 million estimate from the 2021 TRIGA study (inflation adjusted) [2]. This difference is primarily because in 2021, a preliminary and deliberately cautious approach was used to estimate siting and licencing costs on a top-down basis. These estimates have now been updated using the more detailed and bottom-up analysis of such costs undertaken for the 2024 Krško cost study.

2.3. Base case elaboration of cost increases

Table 3 below compares **Base Case in the Krško basin** costs **(without VAT and contingencies)** with the marginal cost increase of adding TRIGA II SNF to the inventory. The final column shows this marginal cost increase as a percentage by level 1 cost area. Note that cost per tonne of heavy metal is not reported since the TRIGA SNF has considerably lower loading than PWR assemblies and would, thus, skew results in an unproductive way.

Table 3: Base Case cost breakdown with marginal cost increases due to

Cost area (level 1)	Cost estimates (in 2023 MEUR) for….		
	Horizontal disposal in sedimentary host rocks at Krško basin	Additional cost for adding TRIGA II SNF to base case	% cost increase
Programme management	52.6	0.14	0.3%
Stakeholder engagement	30.2	0.54	1.8%
Siting	13.7	-	-
Site investigations and RD&D	24.0	-	-
Monitoring	15.9	-	-
Safety assessment, safety case and EIA[5]	4.0	0.12	3.0%
Design	9.1	-	-
Other actions / documents	2.6	-	-
Construction	198.2	0.37	0.2%
Operation and Maintenance	204.7	0.33	0.2%
Closure	18.7	-	-
Institutional control	4.5	-	-
TOTAL	**578.1**	**1.49**	**0.2%**

As shown in Table 3 above, 7 of the 12 major cost areas are unaffected by the TRIGA II SNF addition. Within the affected five cost areas, the key areas of difference are:

- **Stakeholder engagement:** Given the need to transport the TRIGA II SNF from Ljubljana to the Krško basin, where SNF transport was not previously scoped (in this base case), the stakeholder and community engagement budget was assumed to be 10% greater than in the base case.
- **Construction costs:** This cost increase is solely driven by encapsulation facility CapEx for the TRIGA II SNF, which is assumed to occur at the Jožef Stefan Institute spent fuel pool with the need for some additional equipment. This equipment is assumed to cost the equivalent of 1% of the Krško base case encapsulation facility CapEx.
- **Operation and maintenance:** Every level 2 cost area increases for O&M, but most increases are hardly detectable. The most significant increase is in encapsulation facility O&M to encapsulate the TRIGA II SNF into a single canister. Given its unique nature and complexity relative to one of 2282 pressurized water reactor (PWR) assemblies at Krško, this encapsulation O&M increase is assumed equivalent to that of packaging 10 PWR assemblies at Krško. Other increases include cost to transport TRIGA II SNF from Ljubljana to the Krško basin, the added cost of a single canister, and the added cost of one extra day of emplacement O&M to dispose said canister.

These marginal cost increases are explored at a level 2 cost area basis in Table 4 below.

[5] EIA: Environmental Impact Assessment

Table 4: Marginal increases by level 2 cost area with rationale

Cost area (level 1 in bold, level 2 indented)	Base case cost (MEUR)	Cost addition (MEUR)	Percent increase	Rationale
Programme management	52.6	0.14	0.3%	
- Project management	47.5	0.12	0.3%	Maintain 10% of total of various cost areas, including some which increased with the TRIGA addition.
- Licencing	5.1	0.01	0.2%	
Stakeholder engagement	30.2	0.54	1.8%	
- Stakeholder & community engagement	5.4	0.54	10%	Assume a **10% increase** to account for engaging localities in transport path between Ljubljana and the Krško basin.
Safety assessment, safety case, and EIA	4.0	0.12	3%	Assume a **3% increase** for supplemental calculations to validate TRIGA II SNF is bounded by Krško NPP SNF inventory.
Construction	198.2	0.37	0.2%	
- Encapsulation facility CapEx	37.2	0.37	1%	Assume **1% increase** for necessary equipment to package the single canister of TRIGA II SNF.
Operation and maintenance	204.7	0.33	0.2%	
- Disposal canisters	97.9	0.04	<0.1%	Added cost of one **(1) extra canister**.
- Emplacement O&M	26.3	0.03	0.1%	Added cost of one **(1) extra day** to dispose of extra canister.
- Facility O&M	80.6	0.20	0.2%	Assume preparation and packaging the TRIGA II SNF will **equate to O&M for 10 PWR canisters**.
- Transportation of spent fuel	-	0.05	***	Assume a single truck shipment will **cost 50% of a MAGNATRAN shipment** used to ship 12 canisters.

****Transportation of spent fuel was assumed zero in the base case but rose a small amount for the TRIGA addition. Due to this increase from zero, a percent increase is meaningless.*

The effects of these assumptions are illustrated in Figure 1 below, in which the dominant cost areas appear on the left side of the plot. The primary drivers of repository cost in this scenario (and all Krško SNF scenarios) are:

1) **Operation and maintenance**
2) **Construction.**

At this scale of inventory, these two cost areas dominate and would continue to do so for larger inventories, since they would linearly grow. Less significant cost areas such as programme management and closure would also grow with inventory but at a fraction of the rate or volume that O&M and construction grow. Finally, other cost areas such as site investigations and institutional control are considered fixed independent of inventory growth.

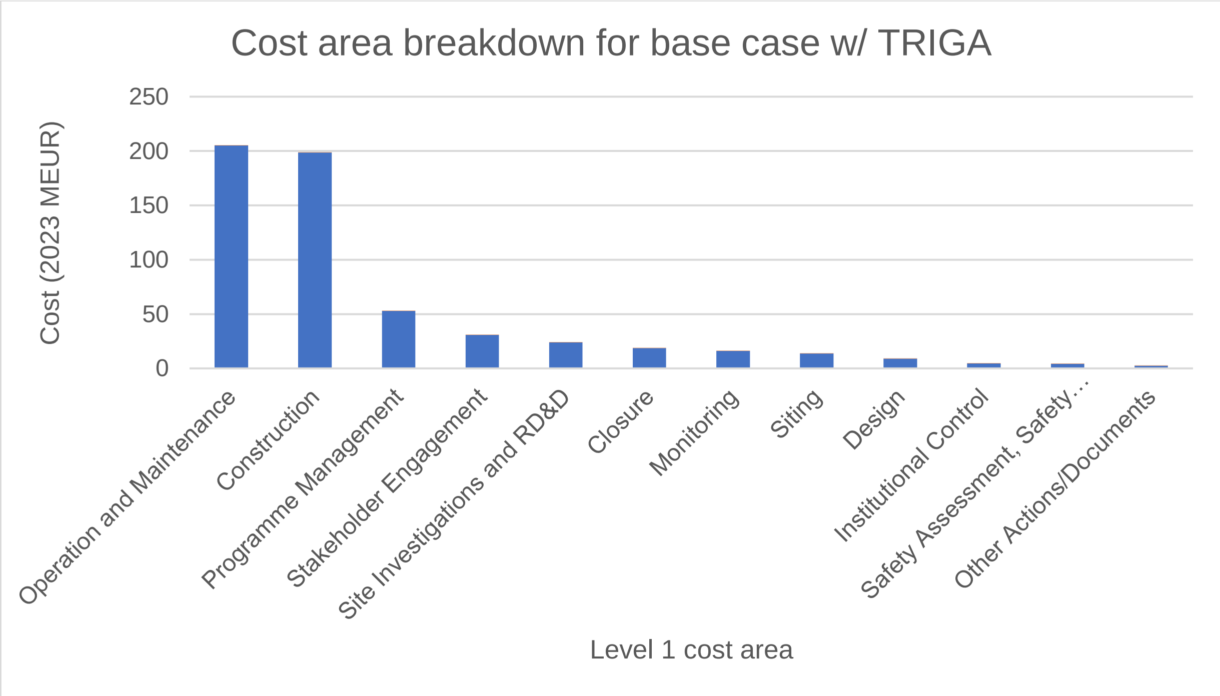

Figure 1: Cost area breakdown for base case with TRIGA addition

Note that if Slovenia were to construct a repository sized for disposal not of the full Krško SNF inventory but only the half that Slovenia owns, the addition of TRIGA II SNF would still only add €1.49M. In such a scenario, the total cost to Slovenia would be €350.8M. Though Krško inventory is halved in this scenario, fixed costs in categories like siting and stakeholder engagement are not assumed to change. Thus, the disposal cost for half of the Krško SNF inventory is considerably more expensive than half of the total Krško cost reported in Table 3 (€289.0M).

3. Standalone TRIGA II repository

3.1. Description and key assumptions

As discussed in the introduction, this study also aims to inform understanding of how deep borehole costs will be distributed in the case of a **standalone borehole for TRIGA II SNF**. Like the TRIGA addition scenario discussed in Section 2 of this document, this standalone TRIGA repository scenario was studied by Deep Isolation in 2021 but was not mapped to the EURAD-aligned work breakdown structure (WBS) developed for the 2024 Krško study. This section maps the standalone TRIGA repository scenario to the EURAD WBS and compares cost areas with the vertical borehole in a generic site base case from the 2024 Krško study. While it is obvious that the generic case from Krško will be exceedingly costlier, there is merit in observing which costs scale linearly with inventory size versus partially or not at all.

Apart from inventory size, many similarities can be drawn between the standalone borehole for TRIGA II SNF and the vertical base case for the Krško NPP inventory (base case b) from the 2024 Krško study). These similarities include:

- **Generic location** away from waste generation site, necessitating **SNF off-site transport**;
- **Vertical borehole architecture**;
  - Though it is worth noting the standalone TRIGA scenario assumes a vertical borehole only extending 1.5 km deep, which makes a sedimentary geology likely as opposed to the crystalline geology anticipated when extending to 3 km in the Krško base case.
- Need for **encapsulation infrastructure**; and
  - Note that whereas the Krško base case assumes that the NPP spent fuel pools will be decommissioned prior to encapsulation, this standalone TRIGA scenario assumes that the Jožef Stefan Institute pools will remain available, necessitating only select equipment for encapsulation.
- Identical **post-closure monitoring** and **institutional control** durations.

3.2. Summary

Section 3.3 below compares the Krško SNF Base Case costs in vertical boreholes in crystalline host rocks in the Krško basin with a single vertical borehole in sedimentary geology for a single canister housing the TRIGA II SNF inventory. These costs (expressed in 2023 Euros for consistency with the Krško study) calculate the actual delivery cost of repository planning, construction, operation, closure, and post-closure institutional control. Other related costs – such as value-added tax (VAT) and contingencies – are then shown additionally in Section 4.

The overall conclusion is that a standalone repository for TRIGA II SNF is significantly cheaper than a repository for the entire Krško NPP inventory at a generic location but not nearly as cost effective as the marginal increase to a Krško NPP inventory repository studied in Section 2 above. These cost comparisons are discussed in greater detail in Section 4. Nearly all cost areas are affected for a standalone TRIGA repository relative to a Krško NPP repository due to the inherently reduced inventory, schedule, and site footprint. Areas in which cost did not change beyond 90% are more influenced by fixed costs, and the extent of fixed versus variable costs are explored in Section 3.3 below. Total lifetime cost for siting, construction, operation, closure, and performing post closure institutional control of the repository in a generic geology of sedimentary host rocks for the TRIGA II SNF is €65.6 million. (a €675 million or 91% cost decrease relative to vertical borehole disposal of the Krško NPP inventory). The 91% cost reduction indicates a largely linear trend but also conveys significant fixed costs given that the TRIGA inventory could fit in one canister as opposed to the 2282 canisters needed for the Krško inventory. In other words, the TRIGA inventory is a 99.96% volume reduction precipitating a 91% cost reduction.

Lastly, it is worth noting that €65.6 million estimate for disposing TRIGA SNF inventory in standalone repository is about 16% more than the €56.5 million estimate from the 2021 TRIGA study (inflation adjusted) [2]. This difference is primarily due to higher fidelity in cost estimates and inclusion of cost items such as community compensation, which were not previously factored into cost.

3.3. Base case elaboration of cost increases

Table 5 below compares the **Krško Base Case for vertical boreholes in a generic location** cost **(without VAT and contingencies)** with the cost of a standalone **vertical borehole in a generic location for the TRIGA II inventory**.

This comparison is not made because the two scenarios at Table 5 are practical alternatives: a repository for Krško SNF is needed regardless of TRIGA II disposal strategy. Nevertheless, by comparing costs of the standalone TRIGA repository with a Krsko-only repository at the identical generic location, this analysis sheds light on the nature of fixed and variable costs in a deep borehole disposal repository. The final column of Table 5 shows how marginal costs decrease as a percentage by level 1 cost area in the case of the smaller inventory – with that reduction being very high where costs are highly variable with inventory size, and much lower in cost areas with a higher proportion of fixed costs.

Table 5: Base Case cost breakdown versus standalone TRIGA repository cost

Cost area (level 1)	**Cost estimates (in 2023 MEUR) for….**		
	Vertical disposal of Krško NPP inventory in crystalline host rocks at generic site	Standalone vertical borehole for TRIGA II inventory at generic site	% cost decrease
Programme management	67.4	6.0	91%
Stakeholder engagement	30.2	9.3	69%
Siting	16.5	10.2	39%
Site investigations and RD&D	26.6	16.0	40%
Monitoring	15.9	3.3	79%
Safety assessment, safety case and EIA	4.0	2.8	30%
Design	15.1	0.6	96%
Other actions / documents	4.0	0.3	92%
Construction	312.5	11.0	96%
Operation and Maintenance	225.5	0.3	>99%
Closure	18.7	1.3	93%
Institutional control	4.5	4.5	-
TOTAL	**740.9**	**65.6**	**91.2%**

As shown in Table 5 above, institutional control is the only unchanged level 1 cost area. Within the remaining 11 cost areas, the key areas of greatest difference (>90% reduction) are:

- **O&M and construction costs:** Given the reduced inventory, these costs largely scaled down linearly until arriving at some level of fixed cost (e.g., transport and drilling a single borehole to a minimum viable depth).
- **Closure and design costs:** Similarly, these costs scale roughly linearly with quantity of boreholes and overall construction-related costs.
- **Other actions / documents and programme management:** These costs also scaled fairly linearly with inventory and schedule. Documentation and security reduced dramatically due to the smaller site footprint and shorter duration for security. Programme management, meanwhile, scaled as a function of many of these aforementioned costs among others.

These marginal cost increases are explored at a level 2 cost area basis in Table 6 below.

Table 6: Marginal increases by level 2 cost area with rationale

Cost area (level 1 in bold, level 2 indented)	Base case cost (MEUR)	TRIGA standalone (MEUR)	Percent decrease	Rationale
Programme management	67.4	5.96	91.2%	
- Project management	61.1	3.00	95.1%	Maintain **10%** of total of various cost areas, including some which decreased with the TRIGA repository.
- Licencing	6.2	2.96	52.5%	
Stakeholder engagement	30.2	9.31	69.2%	
- Community compensation	24.8	3.92	84.2%	Assume compensation only for one (**1**) year pre-repository and for one (**1**) year of a repository operational period (differs from 18- and 4-year assumptions in base case, respectively).
Siting	16.5	10.15	38.6%	
- Refined site evaluation and site selection	11.2	7.85	29.8%	Assume only one (**1**) exploratory borehole (instead of 4 in base case).
- Spatial plan	3.4	0.34	90%	Since only one (1) borehole instead of 10 from a footprint standpoint, assume **10%** of base case cost.
Site investigations and RD&D	26.6	15.98	40%	Assume two **(2) characterization wells** instead of 3.
Monitoring	15.9	3.29	79.3%	
- Pre-operational monitoring	10.2	1.57	84.6%	Assume two **(2) years** of pre-operational monitoring, consistent with EPD (versus 13 years from base case).
- Operational monitoring	4.0	<0.01	99.9%	Assume one **(1) day** of operational monitoring (instead of 4.04 years).
Safety assessment, safety case, and EIA	4.0	2.80	3%	Assume **70%** of base case cost due to the simplified nature of the scenario.
Design	15.1	0.62	95.9%	Maintain **5%** of construction costs, including those affected by changes in this scenario.
Other actions / documents	4.0	0.32	92.1%	
- Investment documentation	0.5	0.10	80%	Assume **20%** of base case cost due to simplified scope of scenario.
- Physical protection (security) plan	3.5	0.22	93.8%	Assume only one (1) year of security (as opposed to 12 years in base case) on a site with existing systems (roads and security). If such systems need to be implemented, cost could increase between €1.8M and €4.4M.
Construction	312.5	10.97	96.5%	
- Drilling	257.3	7.09	97.2%	Since the inventory is so small, assume **50%** of the cost of drilling a **single vertical borehole in sedimentary rock** (since depth will not extend beyond 1.5 km).
- Emplacement infrastructure CapEx	18.0	3.50	80.5%	Assume a single truck at 50% of the cost (since it will handle a reduced capacity). Similarly, assume a single, smaller repository shielded overpack at 50% the standard cost. Lastly, assume only a single drillhole canister dry transfer system.
- Encapsulation facility CapEx	37.2	0.37	99%	Assume **1%** of Krško encapsulation CapEx cost for necessary equipment to package the single canister of TRIGA II SNF.
Operation and maintenance	225.5	0.34	99.8%	
- Disposal canisters	97.9	0.04	>99.9%	Factored cost of one **(1) canister**.
- Emplacement O&M	26.3	0.05	99.8%	Included cost of one **(1) day** to dispose of the single canister.
- Facility O&M	80.6	0.20	99.8%	Assume preparation and packaging the TRIGA II SNF will **equate to O&M for 10 PWR canisters.**
- Transportation of spent fuel	20.7	0.05	99.7%	Assume a single truck shipment will cost **50% of a MAGNATRAN shipment** used to ship 12 canisters.
Closure	18.7	1.32	92.9%	
- Backfilling and sealing	11.9	1.19	90%	Assume one **(1) borehole** to backfill and seal (instead of 10).

-	Surface facility decommissioning	0.6	0.12	80.5%	Maintain **3.5%** of surface facility construction cost.
-	D&D of encapsulation facility	6.1	-	100%	Assume this cost is **beyond scope** and lumped into the Jožef Stefan Institute decommissioning plan.

The effects of these assumptions are illustrated in Figure 2 below, in which the dominant cost areas appear on the left side of the plot. The primary drivers of repository cost in this scenario are:

1) **Site investigations and RD&D,**
2) **Construction,**
3) **Siting, and**
4) **Stakeholder engagement.**

While construction is consistently a cost driver across scenarios (aligning with findings in Figure 1), the heavy influence of the other three cost areas indicates their high fixed costs relative to other cost areas.

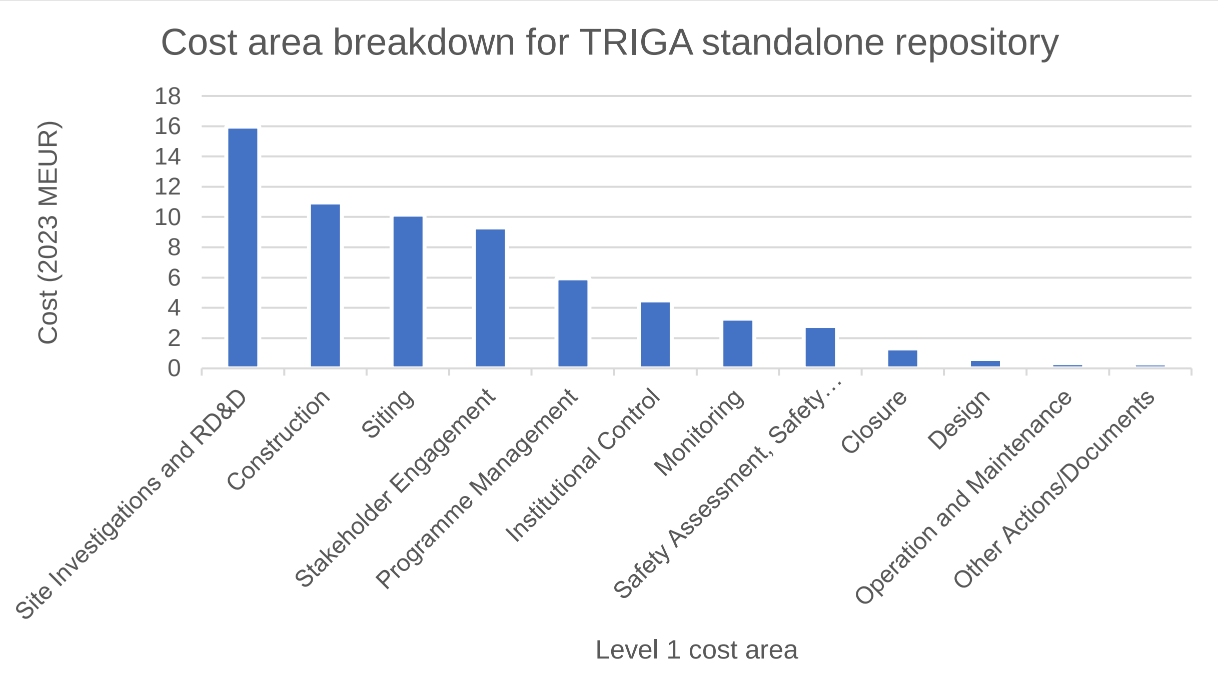

Figure 2: Cost area breakdown for TRIGA standalone repository

4. Sensitivity analysis

The sensitivity analysis on cost utilizes the exact same framework and assumptions used in the Krško study [1]. This approach leverages EPRI methodology [3] and previous technology readiness level (TRL) assessments [4] that have been completed by Deep Isolation. Each phase in the deep borehole disposal process has been assigned a TRL per Deep Isolation's preliminary TRL study[6] [4]. Unsurprisingly, there are no distinguishable differences between the normal distributions plotted in the Krško study and those incorporating a €1.5 million cost increase due to the TRIGA II SNF addition. Therefore, sensitivity data will only be reported in tabular form as shown in Table 7 and Table 8 below. Mined repository costs from a 2024 study by IBE and NAGRA [5] are provided for ease of comparison as they were in the 2024 Krško study.

Table 7: Total cost comparison (excluding VAT) across all scenarios

Cost categories	Cost estimates (in MEUR)					
	Base case w/ TRIGA	EPD w/ TRIGA	ELSC w/ TRIGA	TRIGA Standalone	Mined clay repository from 2024 GDF study	Mined hard rock repository from 2024 GDF study
Subtotal	579.5	495.7	745.8	65.6	1010.2	1216.4
Contingencies	217.8	195.4	285.8	19.7	344.6	427.1
TOTAL	**797.4**	**691.2**	**1031.6**	**85.2**	**1354.8**	**1643.5**

Excluding country-specific VAT, cost savings from Table 7 are largely reflective of those from the Krško study. Specifically, savings are at least 23% cheaper and, in the EPD scenario, up to 49% cheaper than the lowest cost mined GDF estimate.

Table 8: Total cost comparison (with VAT) across all scenarios

Cost categories	Cost estimates (in MEUR)					
	Base case w/ TRIGA	EPD w/ TRIGA	ELSC w/ TRIGA	TRIGA Standalone	Mined clay repository from 2024 GDF study	Mined hard rock repository from 2024 GDF study
Subtotal	579.5	495.7	745.8	65.6	1010.2	1216.4
Contingencies	217.8	195.4	285.8	19.7	344.6	427.1
VAT	118.6	107.4	152.0	12.9	298.0	361.6
TOTAL	**915.9**	**798.5**	**1183.6**	**98.2**	**1652.8**	**2005.1**

All scenarios evaluated in this study are subjected to the 22% Slovenian VAT in Table 8.

Factoring in subtotal, contingencies, and Slovenian VAT, the cases augmented from the Krško study (base case, EPD, and ELSC) each increase by less than €2M. Thus, there is no notable difference in conclusions from the Krško study relative to mined repository costs (e.g., between 27% cheaper for the increased inventory ELSC and 52% cheaper for EPD).

Factoring in all costs, a standalone TRIGA borehole repository would cost around €98M, whereas the addition of the TRIGA SNF to a Krško SNF borehole repository would cost less than €2M. The difference between these two approaches grew significantly with the addition of contingencies and VAT due to the standalone repository incurring more costs in areas which have lower TRLs and are subjected to VAT (e.g., drilling, canisters), whereas the TRIGA addition cases provide minimal additions to such categories.

[6] The following items do not require technology development and were not assigned technology contingencies: Project management, licencing, stakeholder and community engagement, community compensation, initial siting evaluations, safety assessment, safety case, EIA, design, and investment documentation.

5. Conclusions

From this study, we affirm that deep borehole disposal is a cost-effective solution for SNF from the TRIGA II reactor, especially when that SNF is added to a repository for the Krško NPP SNF. Relative to each of the three cases studied for horizontal borehole disposal in the Krško basin [1] (base case, extended lifetime sensitivity case, and earliest possible disposal), scoping in TRIGA II SNF would only add €1.5M. Factoring in contingencies and VAT only raises this cost addition to €1.8M. The main contributors to this small cost increase are community engagement and encapsulation costs associated with activities at and around the Jožef Stefan Institute in Ljubljana, where the TRIGA II reactor is situated.

This study also concludes that a standalone single-borehole repository for TRIGA II SNF would cost considerably more at €65.6M, not to exceed €100M once contingencies and VAT are incorporated. This contrast in costs occurs because, while the TRIGA SNF could fit in a single canister and is thus 0.04% of the Krško SNF volume, many cost areas have significant fixed components. Most notably, site investigations, siting, and stakeholder engagement only scaled down between 38% and 70% relative to the Krško base case.

The safety, compatibility, and schedule of either the TRIGA II SNF addition or standalone repository remain bounded by the findings of the 2024 Krško study. Adding the TRIGA II SNF to the Krško inventory may add one day to overall schedule, while a standalone TRIGA repository could operate on a timeline similar to the Krško EPD case, but with a potentially shorter minimum cooling time and an emplacement duration 4 years shorter. Thus, a combined Krško and TRIGA repository could close as early as 2050 while a standalone TRIGA repository may theoretically be closed as early as mid-2040s. Both of these options significantly outpace mined geological repository closure estimates by several decades.

Lastly, these cost estimates are updates to those provided in a 2021 study [2], and the findings are compared in Table 9 below. These latest estimates leverage a work breakdown structure aligned with the EURAD framework recently implemented in the 2024 Krško study. Though the general conclusions of both scenarios are similar across both studies, the TRIGA addition scenario is considerably cheaper in this study as opposed to the 2021 study. This is largely due to the previous study making more conservative assumptions regarding repository siting and licencing, which are now embedded within the Krško study results. Thus, there is no need for duplication and the net result is a lower cost estimate. On the other hand, the standalone TRIGA repository was shown to be slightly more expensive in this study than in 2021. This is largely due to additional marginal costs in areas like community compensation, which were not accounted for in the 2021 study. Thus, the findings from this study appear to be the more appropriate baseline moving forward.

Table 9: Comparison of cases between 2021 TRIGA study and this 2024 study

Study	Cost estimates (in 2023 MEUR)	
	TRIGA addition to Krško inventory	Standalone TRIGA repository
2021 TRIGA study (inflated)	4.92	56.51
This study	1.49	65.55
% difference	**-69.7%**	**16.0%**

References

[1] M. Waples, C. Parker, E. Bates, J. Midgley, and V. Sharma, “Deep Borehole Disposal for Spent Fuel from the Krško NPP: Cost Study,” Deep Isolation, Mar. 2024.

[2] C. Parker, F. Brundish, K. Moffat, and E. Bates, “Preliminary feasibility study on disposal of TRIGA II research reactor spent fuel using a Deep Isolation repository,” Dec. 2021.

[3] G. Rothwell, “Cost Contingency as the Standard Deviation of the Cost Estimate for Cost Engineering,” *Cost Eng.*, vol. 47, no. 7, Jul. 2005.

[4] E. Bates, M. Frei, J. Midgley, J. Mathieson, and R. Baltzer, “Preliminary Technology Readiness Assessment of Deep Borehole Disposal,” presented at the WM2022, Phoenix, Arizona, Mar. 2022.

[5] “Costing Study for Disposal of Spent Fuel and High-Level Radioactive Wastes from the Krško Nuclear Power Plant in Deep Geological Repository – Multinational Repository,” IBE & NAGRA, Mar. 2024.

