SF and HLW Disposal Planning in Republic of Slovenia

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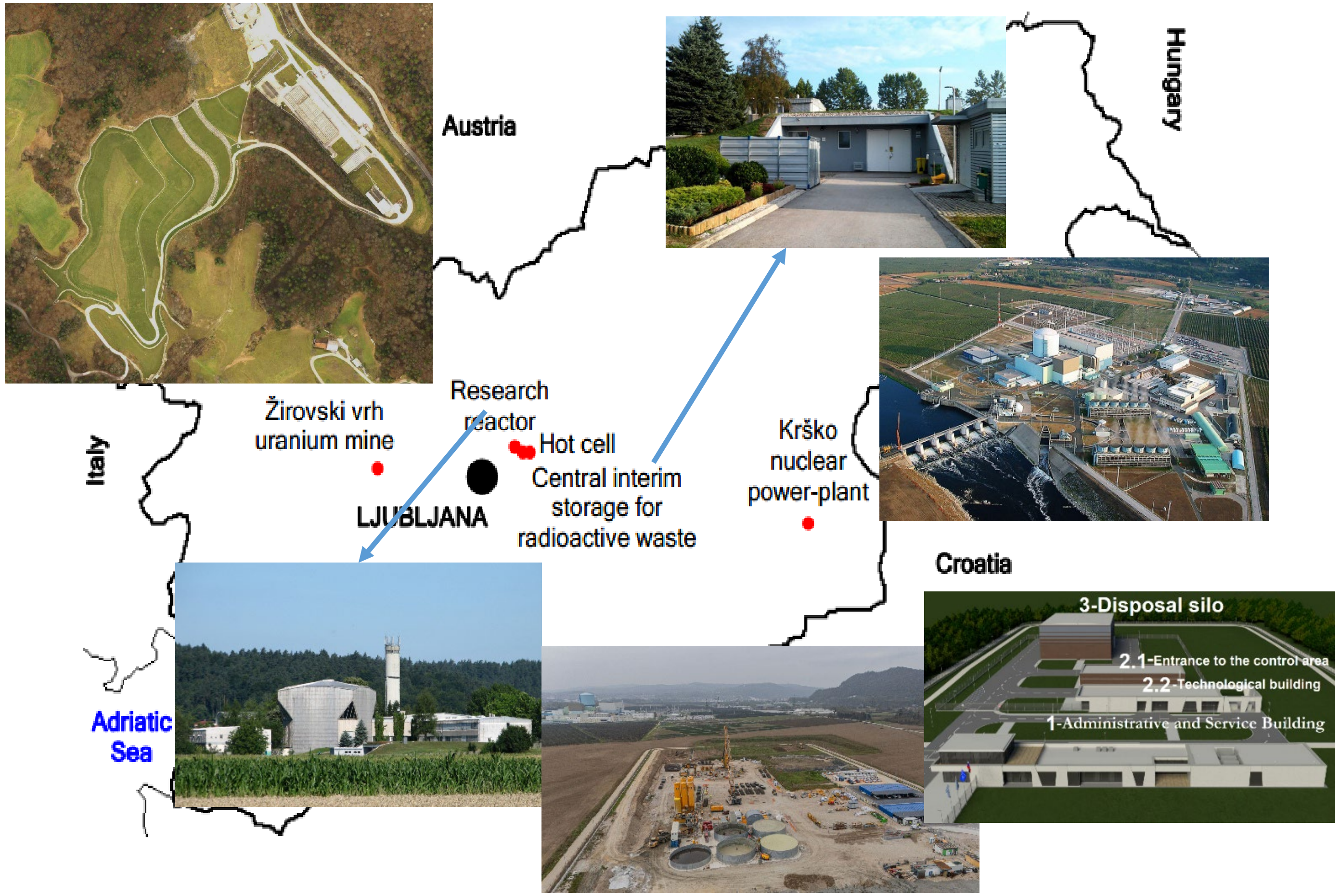
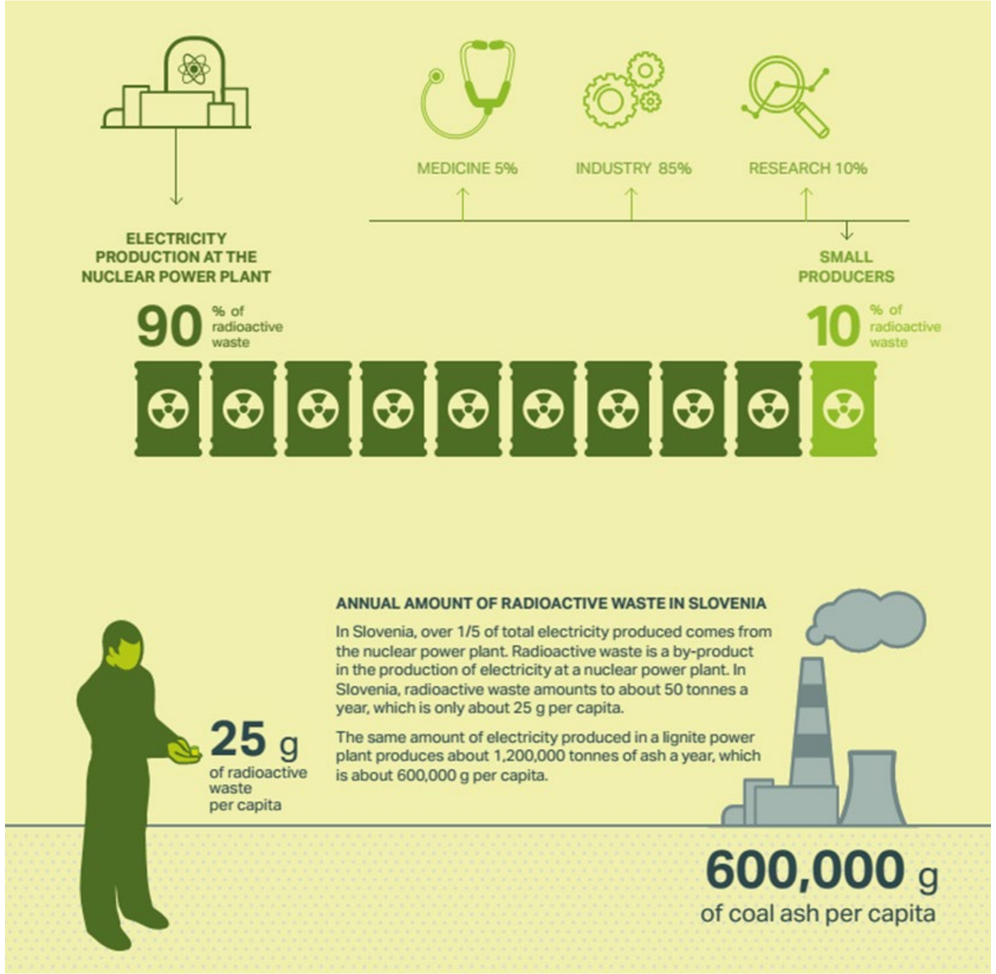
Slovene Nuclear Program - Small Nuclear Program

- *1 NPP, 727 MW_e – electric power; 5 to 6 TWh/y operated by NEK, owned by Slovenia (GEN energija) and Croatia (HEP)*
- *1 research reactor; 250 kW_{th} operated by JSI, owned by RS*
- *1 closed, remediated uranium mine (operation period 1984 - 1990) - 2 disposal sites operated by ARAO, owned by RS*
- *1 central interim storage facility for institutional waste operated by ARAO, owned by RS*
- *1 approved site for LILW repository (2009). In 2022-2023 final construction permit approval and 2023 start of construction.*

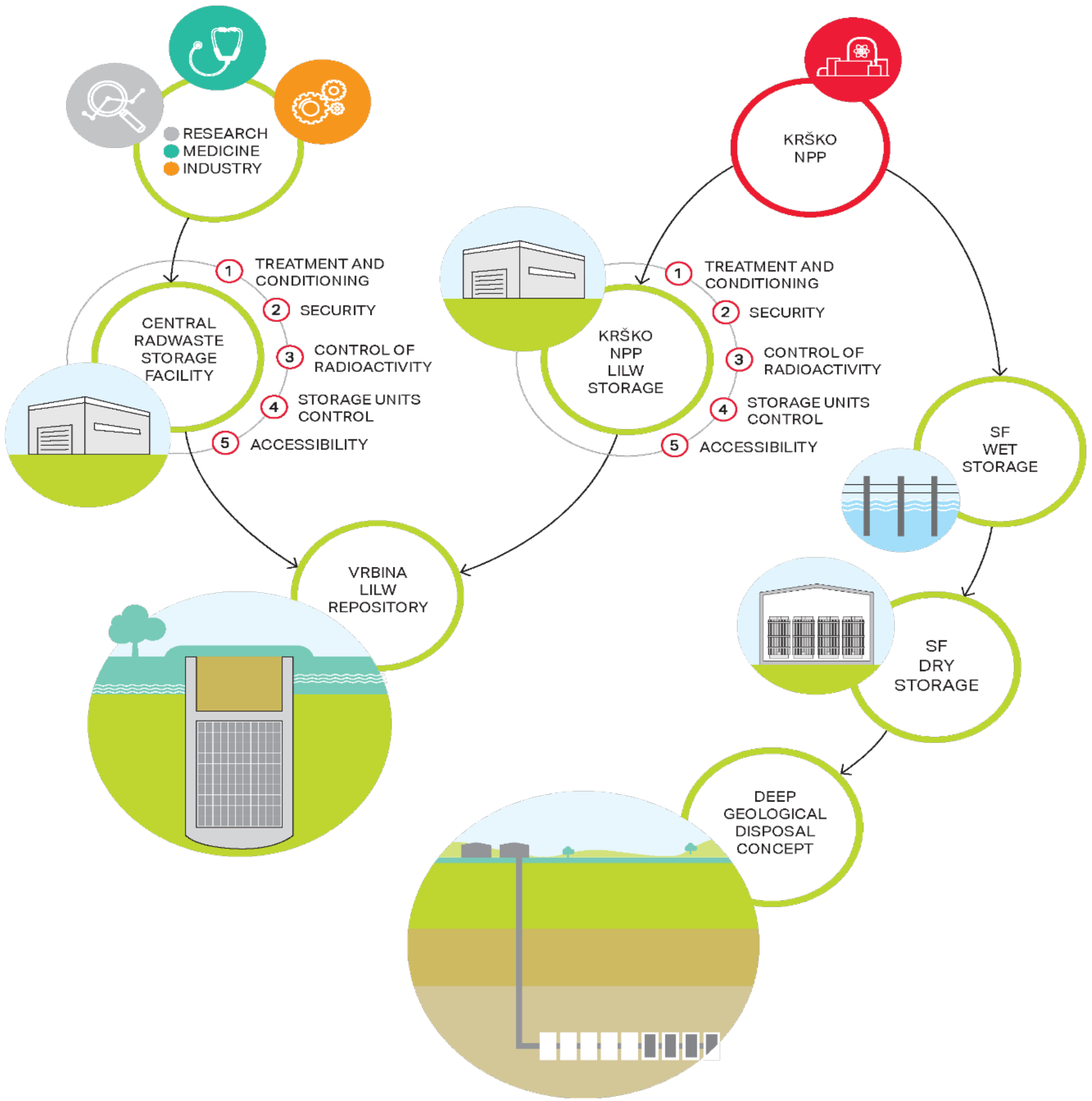


Main Stakeholders in RW&SF Management in Slovenia

- ***Government of Slovenia***
  - *Ministry of the Environment, Climate and Energy (implementer)*
    - *ARAO (WMO)*
    - *Fund for NPP Krško decommissioning and RW&SF disposal*
  - *Ministry of Natural Resources and Spatial Planning*
    - *SNSA (regulator),*
- ***License holders** and **owners***
  - ***Gen energija 50 % owner of NPP Krško***
  - ***HEP (hrvatska elektroprivreda) 50 % owner of NPP Krško***
  - ***JSI,** Ministry of Education, Science and Sport, operator of the TRIGA RR*
  - ***ARAO** – Operator of the Central Storage Facility (CSF)*
- ***Small generators of RW***
- ***Research institutes***
- ***Universities – education and training of experts***
- ***NGOs***
- ***Citizens***



Logical scheme of the National strategy



Nuclear Power Plant Krško

- *Ownership: 50 % GEN energija from RS, 50 % HEP from RC*
- *Krško NPP was constructed as a joint venture between Slovenia and Croatia during 1974 – 1981 period*
- *Westinghouse PWR, 2 loop, 1994 MWt, 727 MWe, in operation since 1983*
- *Lifetime extension till 2043 approved by the owners,SNSA, SEA (successful conclusion of Periodic Safety Review in 2033)*
- *2004 NPP started operating with eighteen-month fuel cycles (½ of core removed -average 56 FA)*
- *Spent fuel (1435 FA) stored in wet spent fuel pool (31/12/2023 SFP – 843 FA) and in SFDS 31/12/2023 – 592 FA*
- *NPP LILW waste managed and stored on site (31/12/2023 2373 m^3)*

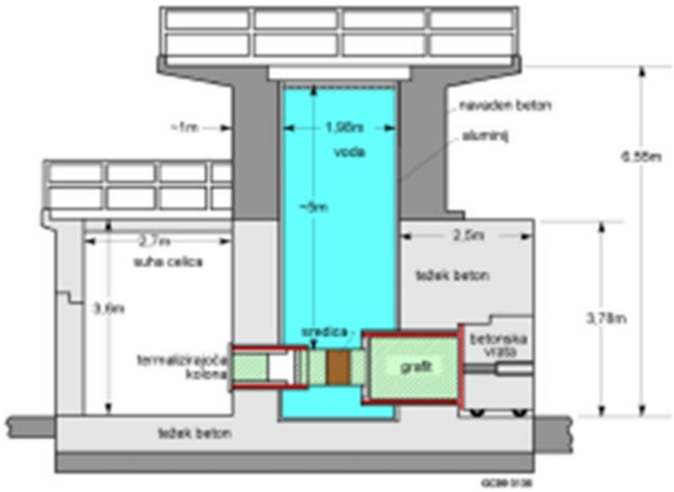
Krško NPP SF and HLW inventory for disposal

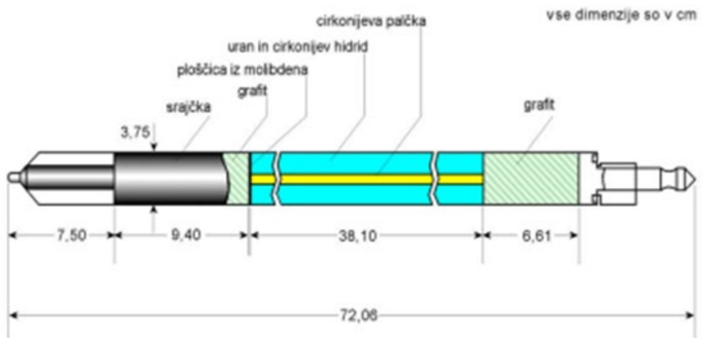
- ***Final shutdown*** *of Krško NPP –* ***2043*** *(Base Case) – total number of fuel assemblies –* ***2282***
- *The average mass of heavy metal in fuel assemblies – 406 kg*
- *Enrichment of the fuel has changed during operation from 2.1 w% in the first core load in the year 1983 to 4.95 w% in the year 2007*
- *For the extended life-time of Krško NPP (2063) – assessed total number of SFA –* ***3182***

	Waste type (HLW or ILW)	Constraining dimension (height x side x side)	Heat generation	Specification	Number of fuel assemblies	Volume (m^3)	Weight (tHM)
Spent fuel from Krško NPP	HLW	3.658 m x 0.19718 m x 0.19718 m	Average burnup rate of 54 GWd/tHM	UOX32 FAs	314	44.7	126
				UOX42 FAs	532	75.7	228
				UOX54 FAs	1436	204.0	569
Total					**2282**	**324.4**	**923**

- *Decommissioning HLW (RPV-Internals), 140 t, Packed in 7 Holtec Non-Fuel Waste Canister (NFWC) and stored in HI-SAFE storage system*

Triga Mark II Operation and Decommissioning Plan





- *Built in 1966, 250 kWt, Part of the JSI Reactor Infrastructure Centre*
- *Purpose: education, research and isotope production*
- *FE: 84 FE (fresh or in the core)*
- *Currently no spent or damaged RR Triga fuel elements. In 1999, all total 219 spent fuel elements were shipped for return to the USA.*

Strategies and programmes for RW and SF management

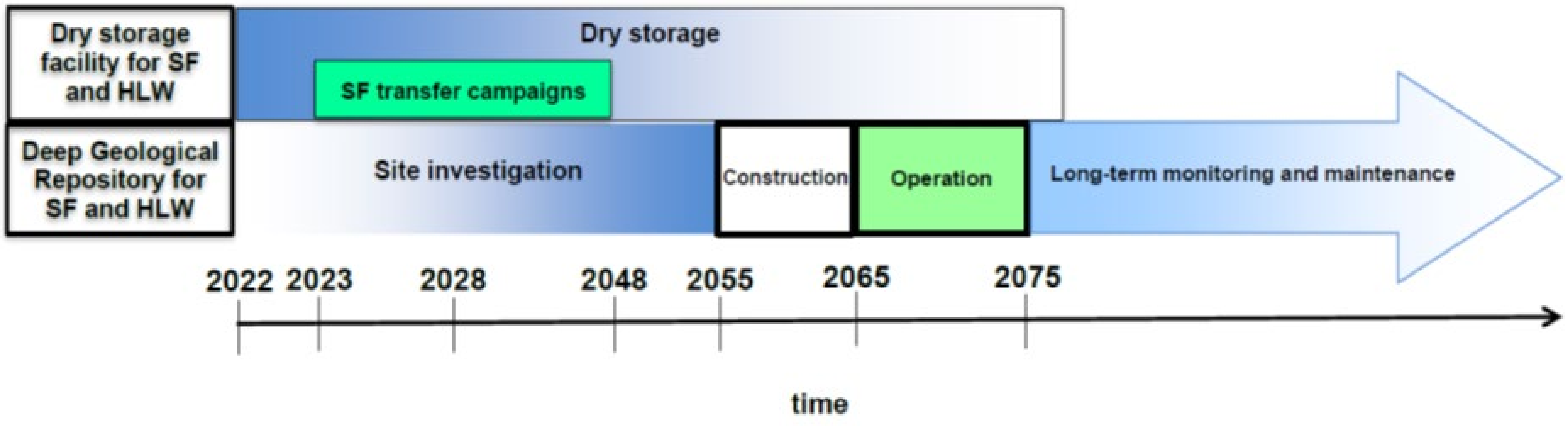
In Resolution on the National Programme for Managing RW and SF for period 2023-2032 (ReNPROIG23-32),

<u>14 strategies </u> *identified for managing different types of RW and SF, decommissioning activities, RD&D activities and activities for long-term control and maintenance of closed or remediated disposal sites:*

- **<u>Strategy nr. 5: SF and HLW storage and disposal</u>**

ARAO shall monitor and participate in international developments in the area of the processing, treatment and final disposal of SF or HLW derived from SF, carry out the necessary activities for the construction of its own SF and HLW repository, and take part in and analyse activities for the disposal of SF in a regional or multinational repository.

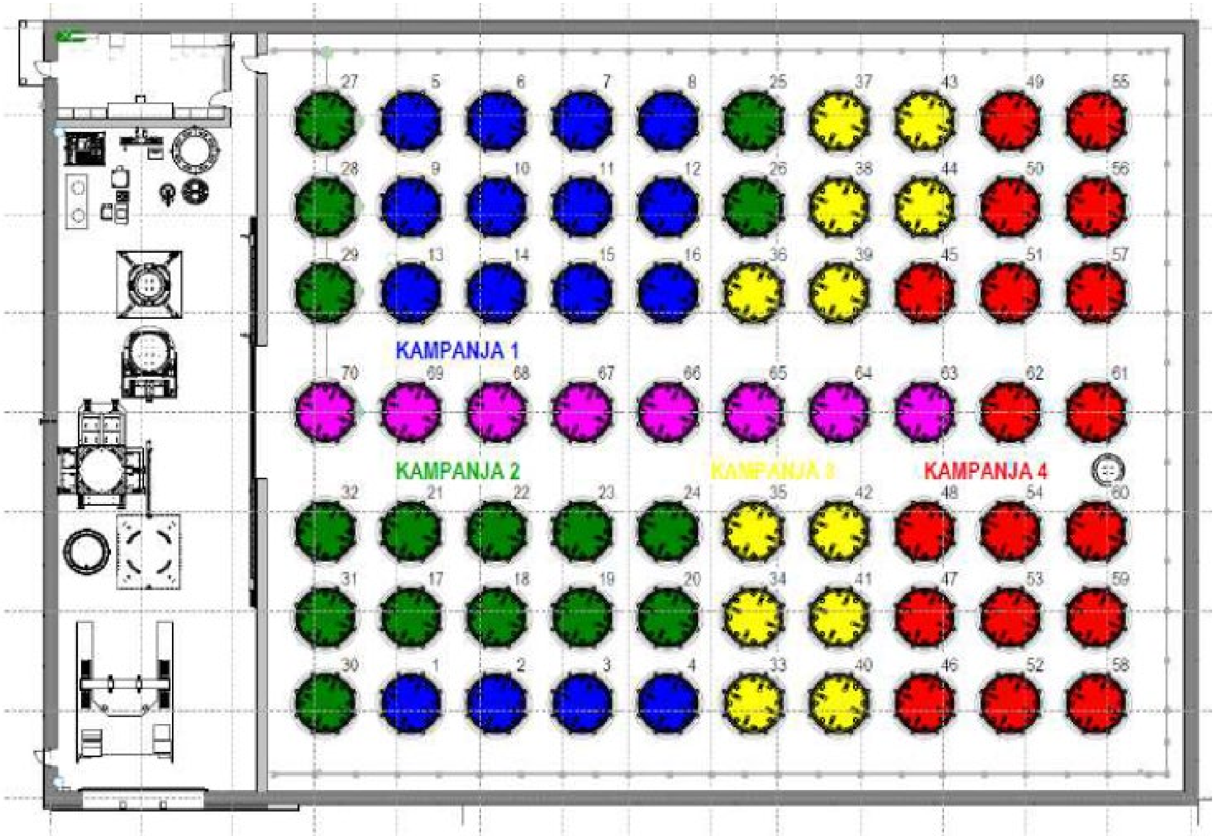
A schematic presentation of the main milestones of Strategy 5



Krško NPP SF management

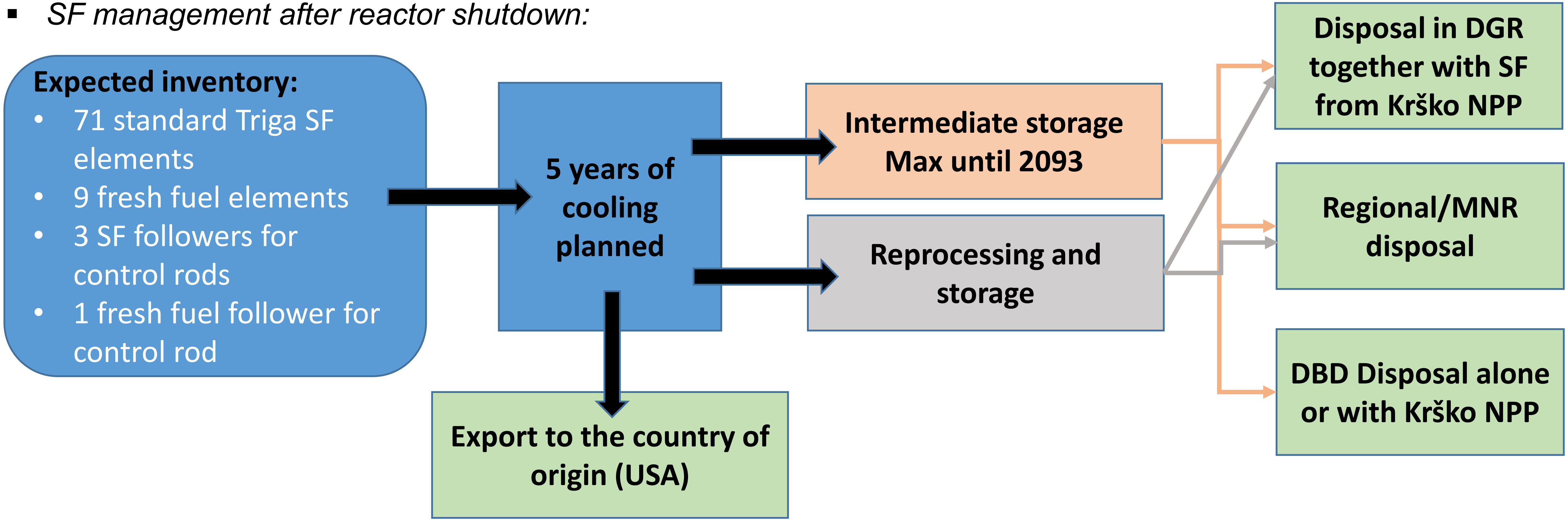
- SFDS building construction 2022-2023, operation March 2023-2103
- 3 SF transfer campaigns – 2023 (finished), planned for 2029, 2048-2051

KAMPANJE POLNJENJA SKLADIŠČA	ŠTEVILO ZABOJNIKOV
KAMPANJA 1	16
KAMPANJA 2	16
KAMPANJA 3	12
KAMPANJA 4	18
REZERVA	8



Triga Mark II Operation and Decommissioning Plan, SF options

- *Operation of the research reactor TRIGA is approved until 2034 with possibility of extension (2043).*
- *Currently no SF, return of 219 SFA in 1999 (USA)*
- *SF return currently not possible – out of scope under Foreign Research Reactor Spent Nuclear Fuel Acceptance Program. Storage capacity available for SF - maintained operational and prepared for immediate use if necessary.*
- *SF management after reactor shutdown:*

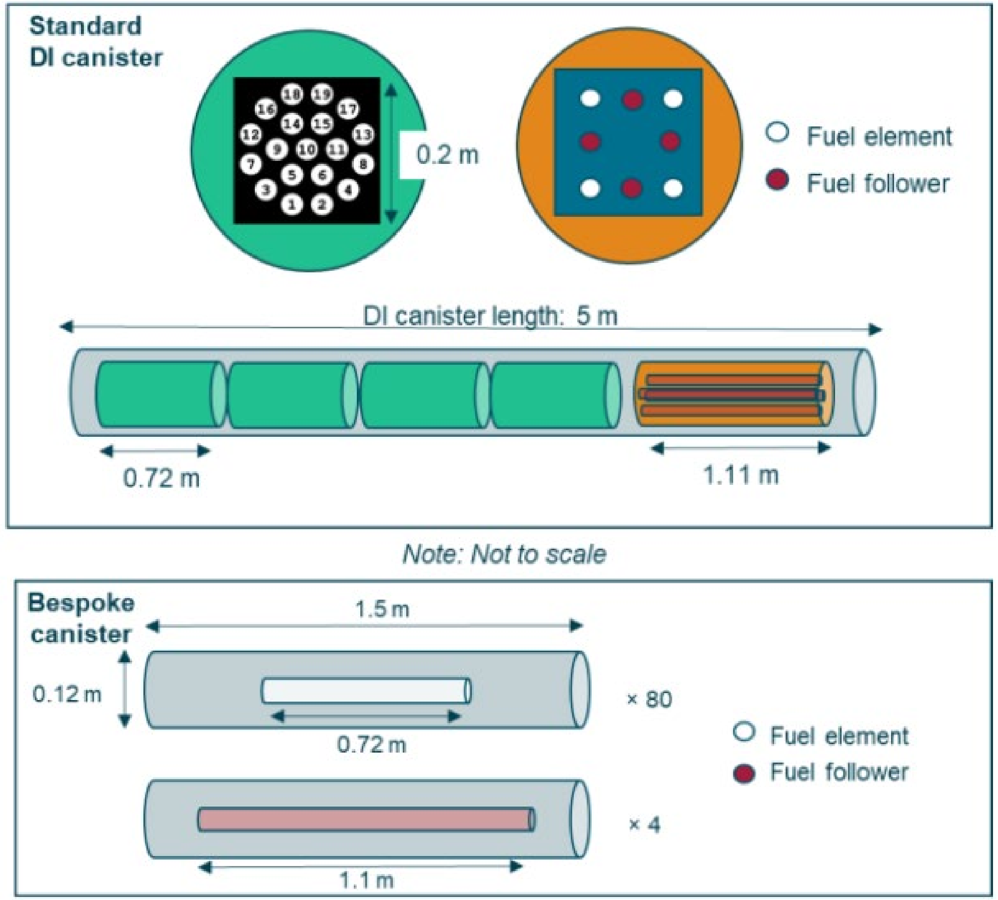


Triga SF Deep Borehole Disposal Option (2021 and 2024)

- Option 1: 1 standard (DI) canister in short vertical borehole drilled to 1,5 km

- Option 2: 1 standard canister in shared borehole repository for Krško NPP SF, **<u>additionally analysed with Krško NPP SNF plans</u>** (2024)

- Option 3: 84 small canisters with narrower disposal zone in horizontal boreholes



- SF potentially suitable for DBD disposal
- The optimum borehole option - larger DBD repository capable also of disposing SF from the Krško NPP

Krško NPP RW & SF Disposal Program Rev.4

- Bilateral Agreement - Croatia and Slovenia have obligation for safe disposal of SF and RW from the Krško NPP operation, maintenance, and decommissioning
- Disposal of SF and HLW – shared project of both countries
- In progress – preparation of 4th revision of the Krško NPP disposal program – a joint project of Croatia and Slovenia
- 4th revision – 3 supporting studies:
    1. **RD&D Program for joint SF and HLW Disposal in DGR in RC or RS**
    2. **Costing study for Disposal of SF and HLW from the Krško NPP in DGR** – Multinational Repository ("dual track" option) included
    3. **Costing study for Disposal of SF and HLW from the Krško NPP - Deep Boreholes Disposal Study (alternative solution!)**
- *IAEA EM: review of concepts, costing and funding, 2024 October*

Costs Work Breakdown Structure

- Work breakdown structure of a geologic disposal programme, as recommended by EURAD ("Guidance on Cost Assessment and Financing Schemes of Radioactive Waste Management Programmes, Aug. 2022)

"Costing Study for Disposal of Spent Fuel and High-level Radioactive Wastes from the Krško Nuclear Power Plant in Deep Boreholes", DI EMEA 2024

- A detailed study of the viability, schedule, and costs of using deep borehole technology to dispose of SF from the Krško NPP
- **DBD costing study only concerns disposal of the SF in deep boreholes,** HLW and LILW-LL disposal analysis will be carried out in the parallel DGR-MNR Project.
- The costings has been generated for a:
    - **Base Case** (**BC**) - NPP Krško lifetime to 2043 and SFDS until 2103 and
    - **Extended Lifetime Sensitivity Case** (**ELSC**), prolonged Krško NPP lifetime to 2063, as well as an extended SFDS operational period, up to 2123.
- SF inventory will be disposed in several deep boreholes at a single location and the SF encapsulation plant will be located at the DBD repository
- No field-based activities to identify and investigate potential sites for a disposal facility will begin until 2050
- High-level geological requirements derived from a generic Slovenian sub-surface lithology and more site specific for data on the geology of the Krško site.

Krško NPP SF DBD: Analysed Scenarios

Selected to evaluate how costs vary across different:

- **Borehole architectures:** horizontal and vertical disposal sections for the repository.
- **Geology:** sedimentary rock and crystalline rock
- **Location:** Krško itself, and a 'generic' location with geology typical of much of Slovenia and Croatia.
- **Timetables:** The study looks at two scenarios:
  - ➢ a **Base Case** where disposal begins 30 years after reactor shutdown in 2043,
  - ➢ an **Extended Life Sensitivity Case** in which the NPP's life continues to 2063
  - ➢ …. and an additional **Earliest Possible Disposal Case**.

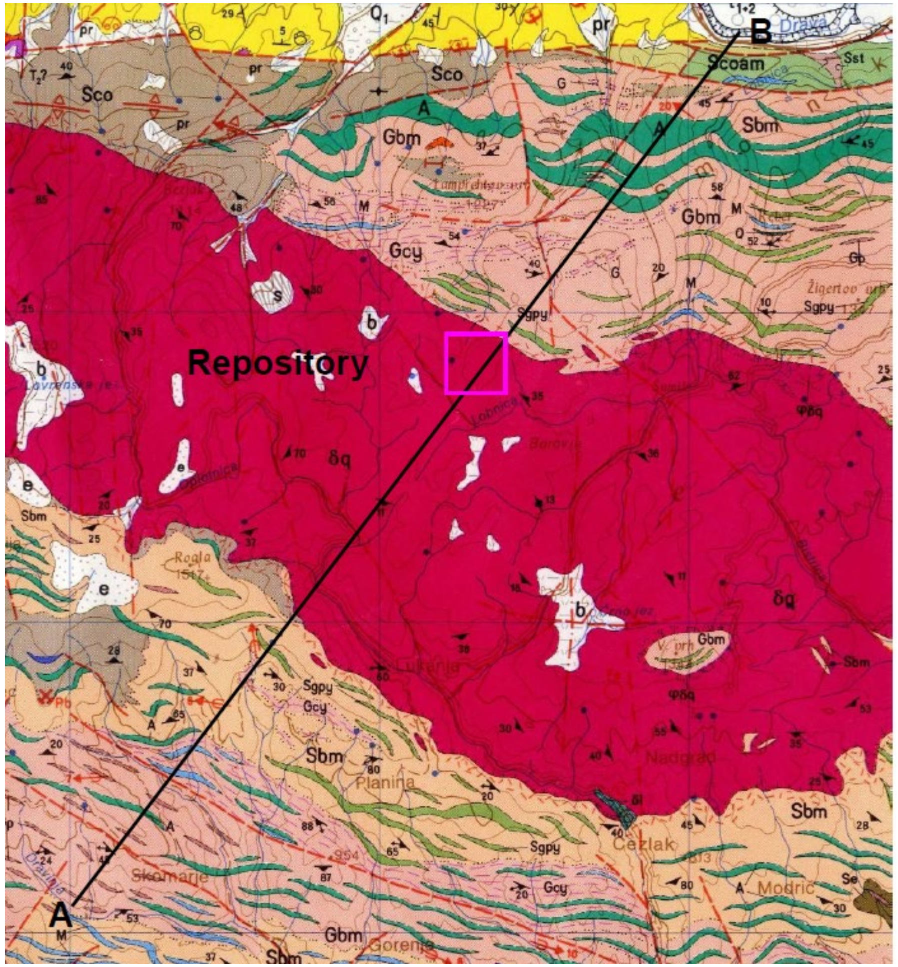
24 possible combinations, simplified into 9 scenarios for this analysis

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

Key: ● Full costed scenario using EURAD Work breakdown structure
○ Top-level analysis of key cost differences

Krško NNP SF and HLW disposal – mined DGR

- *SFDS at Krško NPP enables safe and cost-effective storage of all planned SF and HLW inventory for at least 60 years after Krško NPP shutdown*
- *For final SF&HLW disposal, a dual-track policy has been adopted as the appropriate solution in the present situation. The dual-track approach in the Slovenian strategy includes both the option of multinational or regional disposal and a basic reference scenario for national geological disposal.*
- **<u>Deep Geological Disposal facility:</u>**
  - Shared RS&RC disposal for Krško NPP SF inventory
  - Reference scenario for disposal in RS or RC in hard rock environment with 500 m depth based on KBS-3V prepared as basic scenario (2004, 2009, 2019, 2024)
  - Main drivers: cost estimates, KBS-3V koncept used as the most advenced and comparable, basis for siting, RD&D plan, analogy with LILW repository used for required procedures development, …
  - In 2024 DGR costing study in sedimentary formations prepared
  - Geo data and preliminary catalogue of argillaceous formations for DGR disposal prepared



RD&D Program for joint SF and HLW Disposal in mined DGR in RS or in RC

- 2024 first version of the joint RD&D Program with guidelines, revisions every 5 years - amendments with time.
- An overall plan for the DGR site selection process:
    - Analysis of the existing studies, references, legislative background and other documentation
    - Proposal for the site selection criteria (exclusionary, comparative)
    - Proposal of the site selection methodology, process, procedures and technologies
- *Base line (Krško NPP 2043, DGR in 2093) and 2 sensitivity scenarios*
- *Organization of the RD&D Program implementation*
- *Communication Support and Stakeholder Engagement*
- *Pre-operational monitoring, RD&D Program timeline, RD&D Program cost estimation*
- *The whole RD&D Program has more than 400 pages, with detailed description of methodology, milestones, cabinet studies, additional plans, investigative techniques and proposed organization*

RD&D Program for HLW&SF from Krško NPP

Proposed stages of the DGR site selection process:

1) ***Initial survey of the territory of both countries*** *(RC and RS), which will result in the identification of "geologically" suitable regions (primarily – desk study)*
2) ***Narrowing of suitable regions*** *to the level of suitable subregions*
3) ***Screening for suitable areas****, and therefore reducing subregions to suitable areas*
4) ***Selection of potential sites*** *within the suitable areas (up to ten or more)*
5) ***Selection of candidate sites*** *(one in RC and one in RS)*
6) ***Selection of the final (host) site*** *(not a part of RD&D program)*

CONSENT BASED - VOLUNTEERING APPROACH

"Call for volunteers" can be done after:

- after step 3 (when suitable areas are known, and hence municipalities on the suitable areas)
- after step 4 (when potential sites are known)

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Costing Study for Disposal of Spent Fuel and High-level Radioactive Wastes from the Krško Nuclear Power Plant, 2024

Scenarios (ToR):

Base Case *(BC) scenario: Krško NPP up to 2043, SFDS up to 2103/2107*

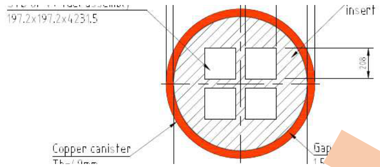
- **a. DGR scenario**: SNF, HLW, LILW-LL, disposed of in a single DGR, in Slovenia or Croatia
  - **i. Hard rock DGR scenario**
  - **ii. Sediment DGR scenario**
- **b. MNR scenario**
  - i. Shared MNR:
    - 1. Hard rock DGR – KBS-3V
      - a. Krško inventory 10 %
      - b. Krško inventory 25 %
      - c. Krško inventory 50 %
    - 2. Sediment DGR – OPA
      - a. Krško inventory 10 %
      - b. Krško inventory 25 %
      - c. Krško inventory 50 %
  - ii. Commercial MNR
- **c. DGR scenario (without SNF) for HLW and LILW-LL**
  - i. DGR at DBDF
  - ii. DGR at separate site

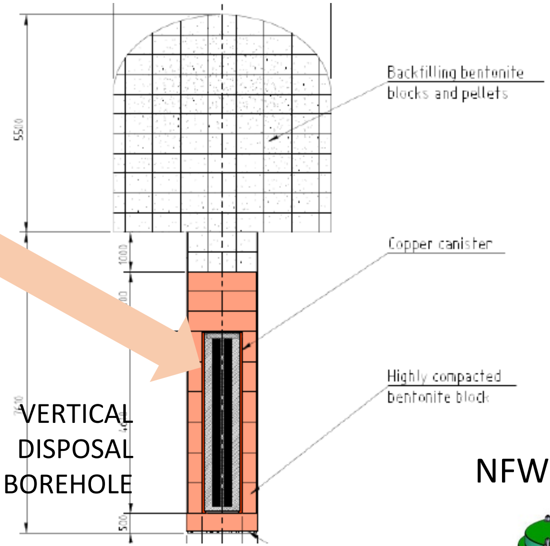
Extended Lifetime Sensitivity Case (ELSC): Krško NPP up to 2063, SFDS up to 2123

Disposal concepts

Hard rock: KBS-3V concept (SKB, Sweden)

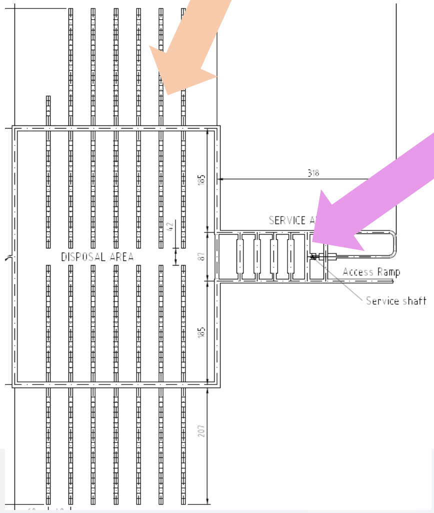
Disposal canister



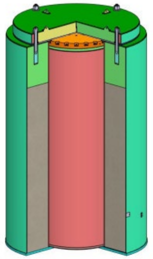


VERTICAL
DISPOSAL
BOREHOLE

Specific solutions for hard rock concept

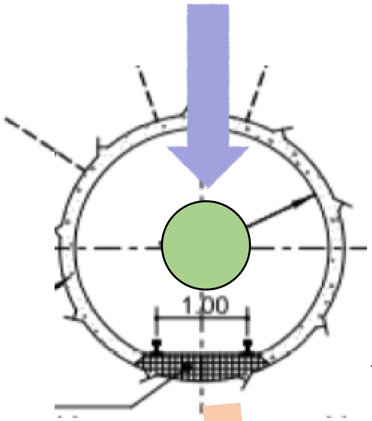


HLW
NFWC/HI-SAFE

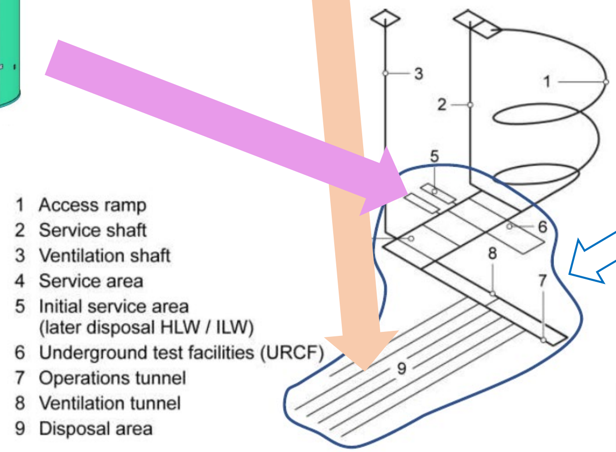


Clay: Nagra concept (Switzerland)

Disposal canister without Cu lining



HORIZONTAL
DISPOSAL
TUNNEL



Specific solutions for clay geological environment

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Main(key) differences in both DGR scenarios

Differences between the two concepts that significantly affect the costs:

1. *Steel disposal canisters for clay disposal are significantly less expensive than hard rock disposal canisters that are lined with copper.*
2. *Excavation and construction of an access (access ramp, service shaft and ventilation shaft) to the disposal part of the DGR in the sediments is less expensive (for approximately 20 %) than excavation and construction to the disposal part in hard rock.*

Component	**DGR BC Hard rock**	**DGR BC Clay**
	Volume (m^3)	
Access ramp	240,000	
Service shaft	13,250	
Ventilation shaft	4,500	
Service area	74,660	24,902
Access/operational/ventilation tunnel	106,674	24,386
Disposal tunnels (571 canisters)	180,576	39,330
Disposal boreholes	11,037	N/A
Rock specific excavation volume	372,947	88,618
Total excavated rock volume	**630,697**	**346,368**
Disposal tunnels/boreholes	28 disposal tunnels of 207 m / 21 boreholes per tunnel.	5 disposal tunnels of 800 m.
	Tunnel No. 28: 54 m/4 boreholes.	Tunnel No. 6: 600 m.

Costing of HLW and SNF disposal, 2024

- *Costing of HLW and SNF disposal based on EURAD WBS structure and used for mined DGR and DBD:*
  1. Disposal programme management
  2. Stakeholder engagement
  3. Siting
  4. Site investigations and RD&D
  5. Monitoring (from baseline information to long-term safety of the repository)
  6. Safety Assessment, Safety Case and Environmental Impact Assessment
  7. Design
  8. Other actions / documents
  9. Construction
  10. Operation and maintenance
  11. Closure
  12. Institutional control

		Base cost (EUR)	Inaccuracy (%)	Surcharge (EUR)	Hazard (%)	Surcharge (EUR)	Total cost (EUR)
9.5	Underground structures	239.299.199		59.824.800		47.859.840	346.983.839
9.5.1	Access ramp	97.131.173	25%	24.282.793	20%	19.426.235	140.840.201
9.5.2	Service shaft	6.169.851	25%	1.542.463	20%	1.233.970	8.946.284
9.5.3	Ventilation shaft	2.466.730	25%	616.682	20%	493.346	3.576.758
9.5.4	Service area with URCF	11.165.341	25%	2.791.335	20%	2.233.068	16.189.745
9.5.5	Operations and ventilation tunnel	11.396.316	25%	2.849.079	20%	2.279.263	16.524.659
9.5.6	Disposal tunnels	110.969.788	25%	27.742.447	20%	22.193.958	160.906.193

- *Each of the groups was further subdivided in more detailed and specific cost items, such as:*

  9. Construction
     - 9.1. Construction management
     - 9.2. On-site and offsite infrastructure
     - 9.3. Above-ground facilities and structures
     - 9.4. Construction of an underground research facility (URF)
     - 9.5. Underground facilities and structures
     - 9.6. Other disposal facilities or services (e.g. encapsulation plant)
     - 9.7. Installation of equipment.

  - *Cost estimates are made for each individual WBS item down to 3rd level (e.g. 9.5.6 Disposal tunnels).*
  - *To base costs, surcharges for inaccuracy and risks were added using the STENFO methodology (up to a maximum of 50% of base costs).*

Conclusions, Challenges and Opportunities

- Studies and Program (RD&D) prepared/updated for SF and HLW disposal (mined DGR and DBD)
- Currently, due to ReNPROIG 23-32 defined key milestones and especially due to construction of LILW repository only generic locations and parameters are used
- ARAO will continue to develop plans, design, siting, RD&D activities,… for mined DGR
- Criticality analyis of the SF repository from the Krško NPP started 2025-2028, a catalogue of argillaceous formations will be developed/updated, preliminary DGR PA/SA, initial RD&D activities will start
- ARAO will continue to monitor progress of DBD option

Thank you for your attention!