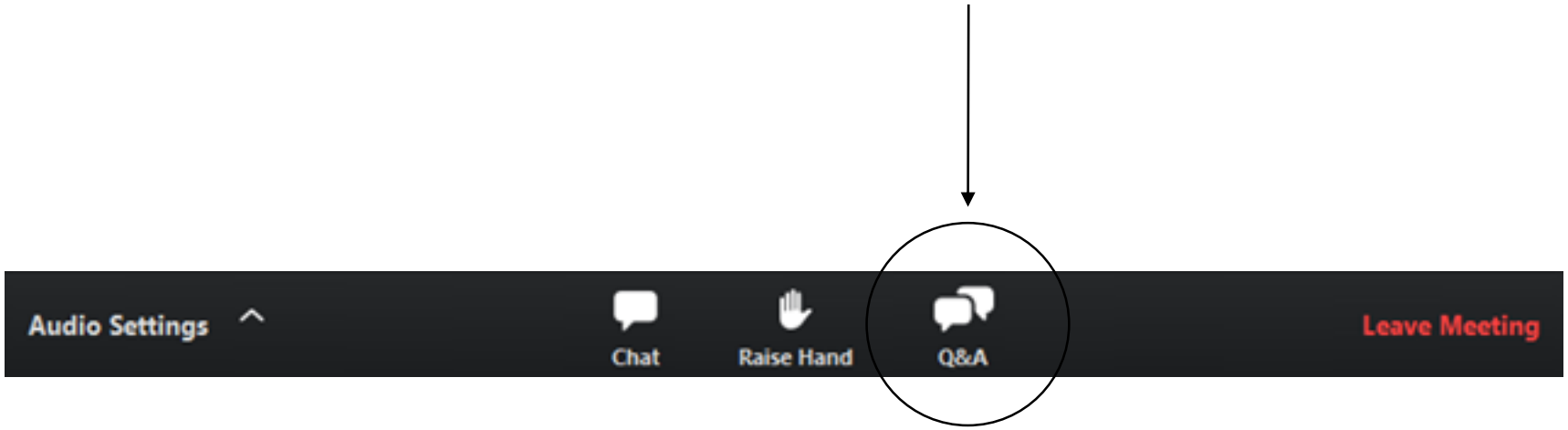
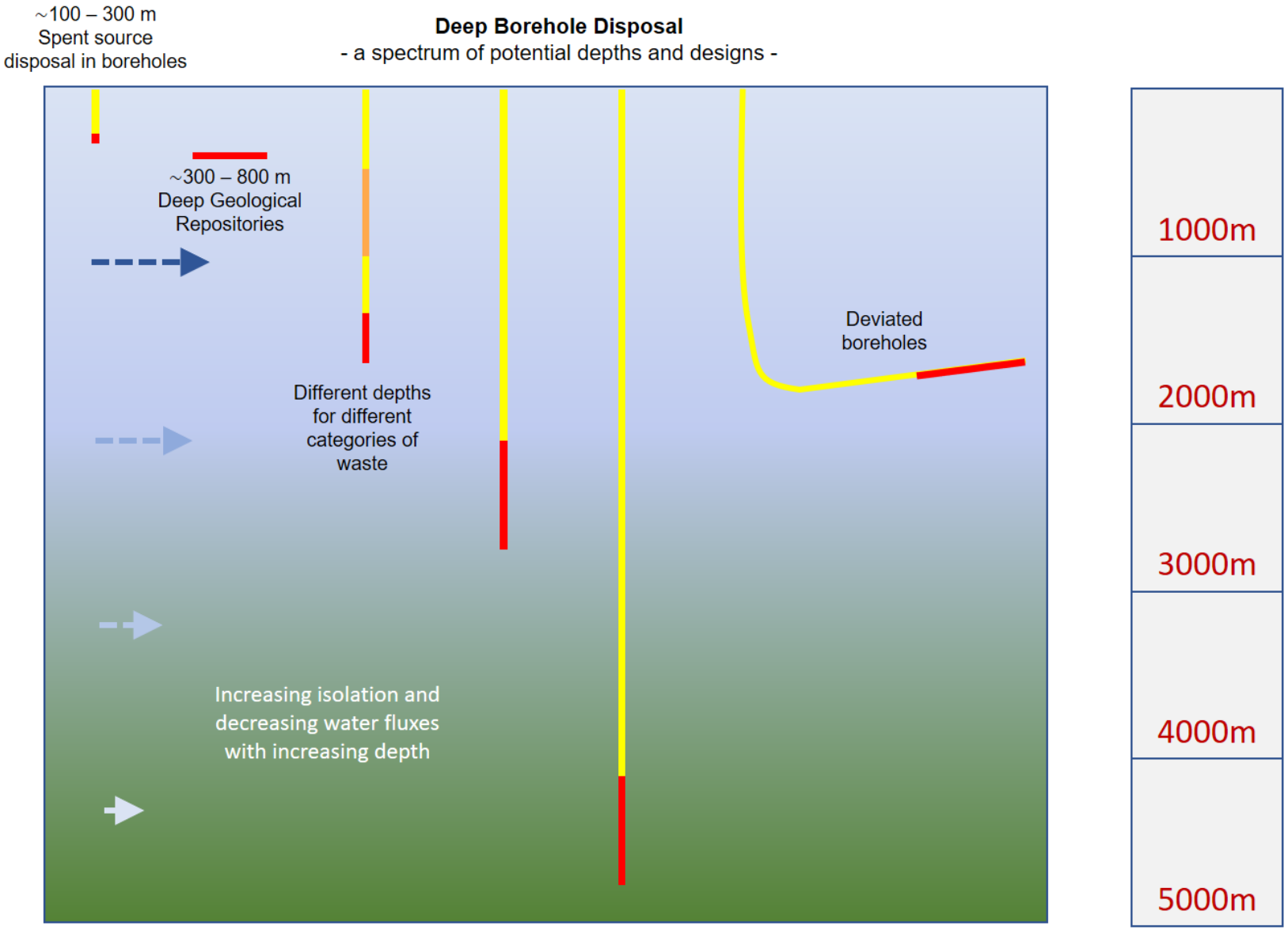
Welcome !

To ask a question, please use the Q&A section.



Deep Borehole Disposal
- a spectrum of potential depths and designs -



Thursday, November 5 14h00/15h30 CET

Panel on Current Deep Borehole Activities with Additional Perspectives

1. **Deep Isolation, Inc., Chris Parker** Deep Isolation is the leading deep borehole disposal commercial concern. The presentation will address their technology and activities.

2. **Havard Kristiansen, Norwegian Nuclear Decommissioning agency (NND)** will provide a presentation on the work being done for the ERDO Working Group on this subject (led by a project being developed in Norway).

3. **Dirk Mallants of the Commonwealth Scientific and Industrial Research Organization (CSIRO) Australia** will discuss their program for evaluating this technology for application in Australia.

4. Over time several countries have expressed interest in this disposal approach, including Croatia, Jordan, Slovenia, UK, Sweden, Denmark and others. There will be an opportunity for WG members to comment on any work they have done, or provide their perspective on this technology.

5. **Moderator led panel discussion.**

DEEP ISOLATION

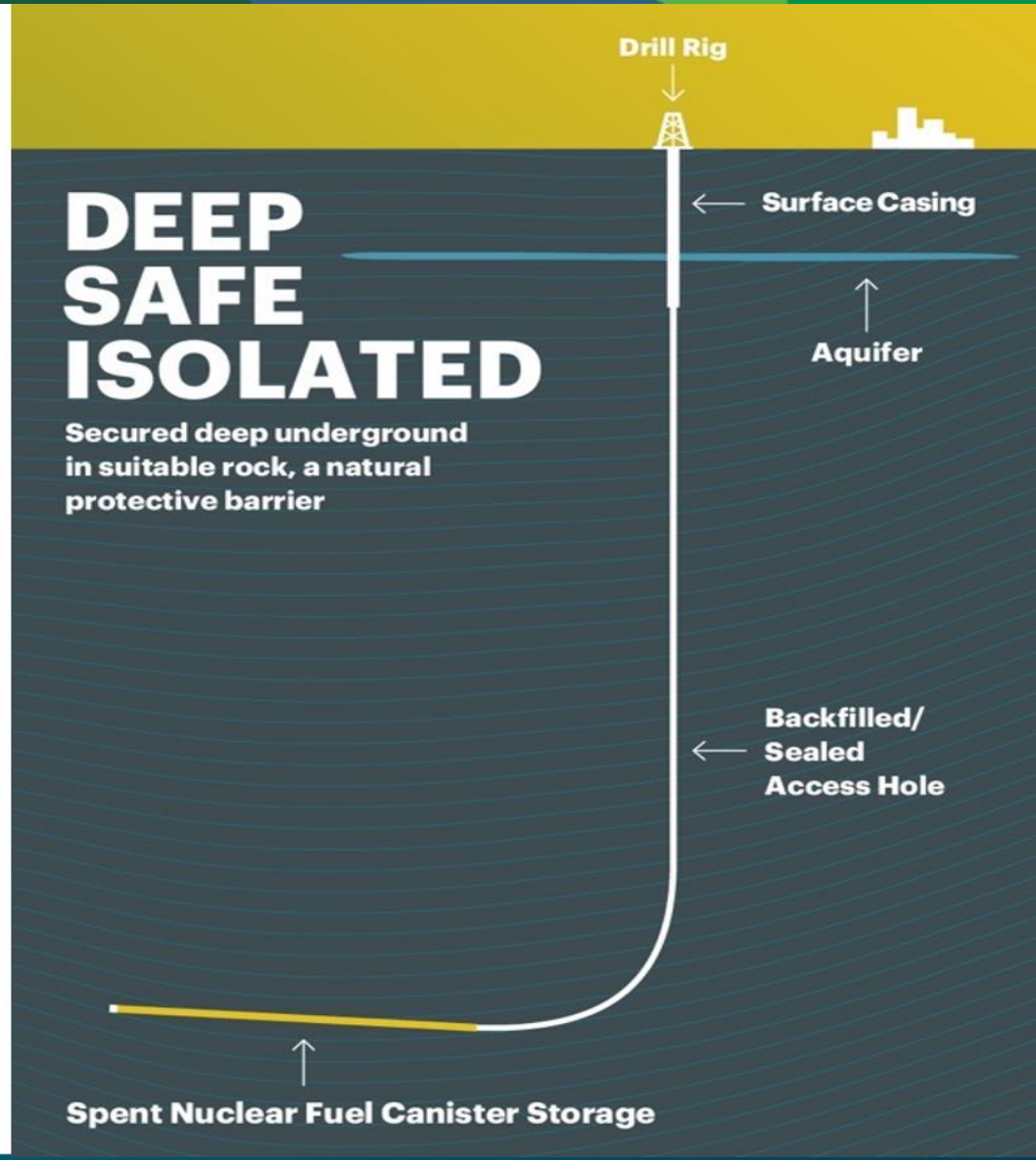
Disposal of nuclear waste in directionally-drilled boreholes

Overview for IFNEC
5 November 2020

DEEP ISOLATION

What I will cover today

- Directionally-drilled borehole disposal and how it works
- The key benefits:
  - ✓ Safe
  - ✓ Equitable
  - ✓ Affordable
- Case study: the UK NDA

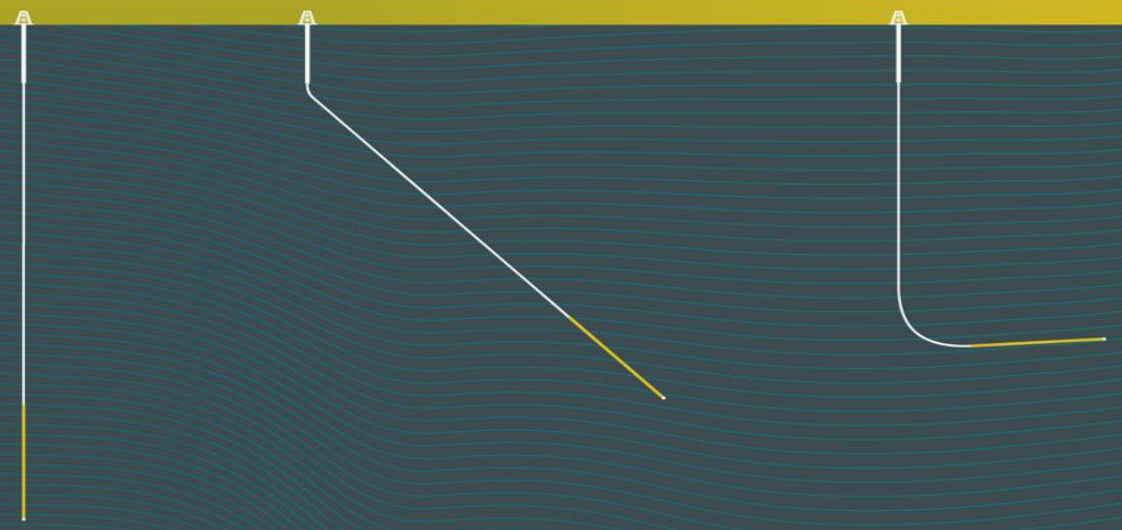


How it works

DEEP ISOLATION

Horizontal disposal creates new opportunities

- Directional drilling allows us to tailor repository design for the needs of a specific inventory and specific geology
- Optimal might be vertical, deviated or horizontal – our partnerships, supply chain and our IP support all of these



Horizontal boreholes:

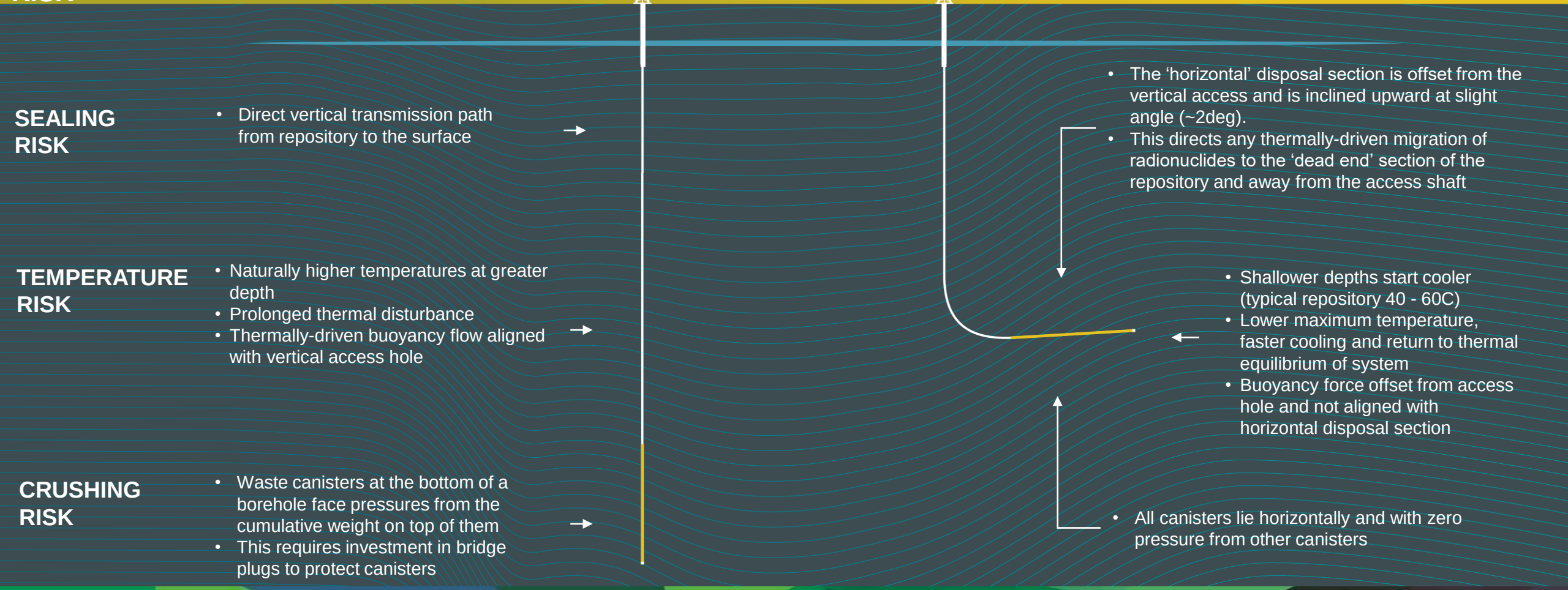
- ✓ Deliver high levels of safety combined with cost benefits
- ✓ Address many concerns that have led some governments and regulators to steer clear of disposal in traditional vertical boreholes

Passive features of a horizontal repository offer solutions to concerns raised about borehole disposal

OPERATIONAL RISK

- A dropped canister will impact canisters already emplaced with risk of damage

- A dropped canister will decelerate in the curved section, drifting safely to a halt prior to the repository



SEALING RISK

- Direct vertical transmission path from repository to the surface

- The 'horizontal' disposal section is offset from the vertical access and is inclined upward at slight angle (~2deg).
- This directs any thermally-driven migration of radionuclides to the 'dead end' section of the repository and away from the access shaft

TEMPERATURE RISK

- Naturally higher temperatures at greater depth
- Prolonged thermal disturbance
- Thermally-driven buoyancy flow aligned with vertical access hole

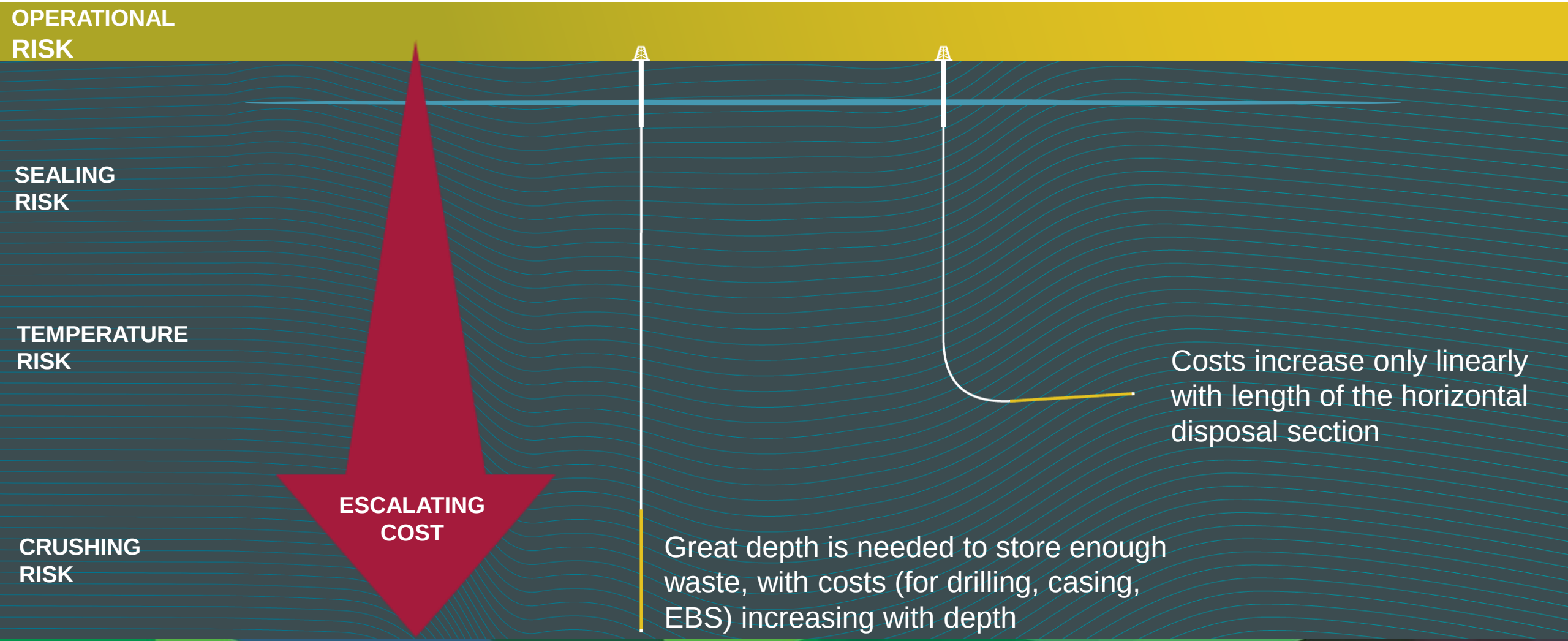
- Shallower depths start cooler (typical repository 40 - 60C)
- Lower maximum temperature, faster cooling and return to thermal equilibrium of system
- Buoyancy force offset from access hole and not aligned with horizontal disposal section

CRUSHING RISK

- Waste canisters at the bottom of a borehole face pressures from the cumulative weight on top of them
- This requires investment in bridge plugs to protect canisters

- All canisters lie horizontally and with zero pressure from other canisters

Marginal costs of a horizontal repository do not keep growing with the size of inventory for disposal



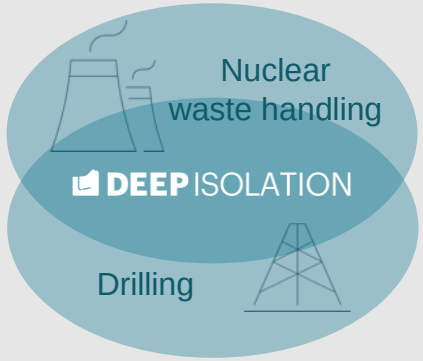
Developing an innovation ecosystem to tackle a global problem

1 Innovation

- 40+ inventions, with 38 US and international patents granted and in development:
  - Formation suitability
  - Repository Design
  - Canister Design
  - Handling, Emplacement, & Retrieval
  - Monitoring
- Most support all borehole architectures, some are specific to vertical or horizontal

2 Open and peer-reviewed science

3 World-class supply chain



BECHTEL

NAC INTERNATIONAL

Schlumberger

4 Inter-disciplinary, cross-sector stakeholder engagement

universities
collaboration
NGOs
partners
communities
local government
civil society
green energy
citizens
municipalities
oil & gas
environment
research institutes
schools
nuclear
National Geological Surveys

5 Client collaboration

- Perhaps most importantly, we are now deeply engaged with potential clients and partners around the world – including many national radioactive waste management organizations
- Key focus of this engagement:
  - Waste inventory review
  - Geological suitability
  - Regulatory pathways
  - Local economic development impacts
  - Stakeholder engagement processes

The key benefits

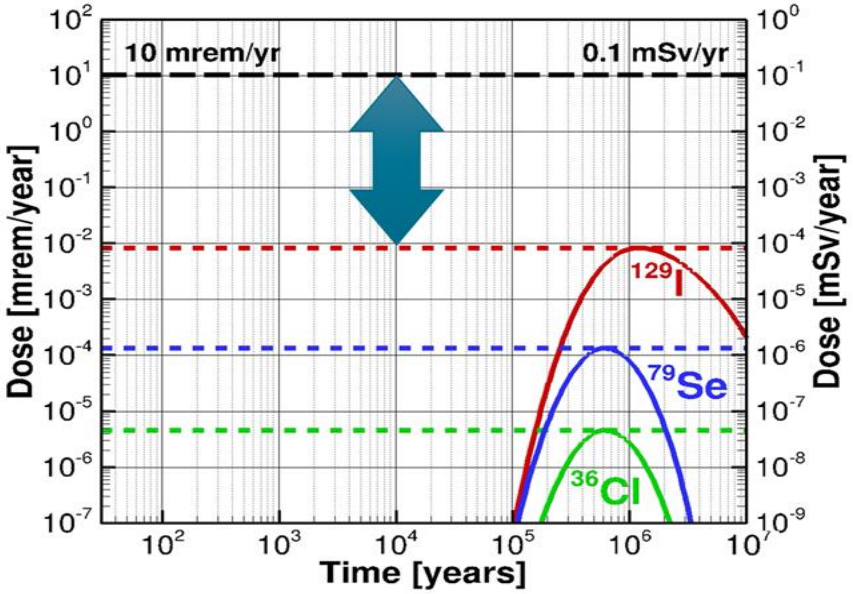
Safe, equitable, affordable

DEEP ISOLATION

A Safe Solution

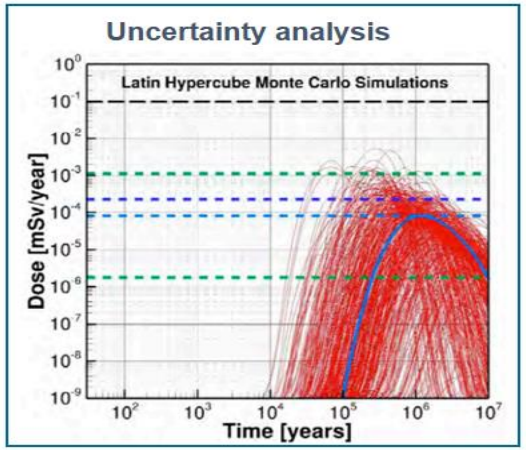
GEOLOGIC ISOLATION

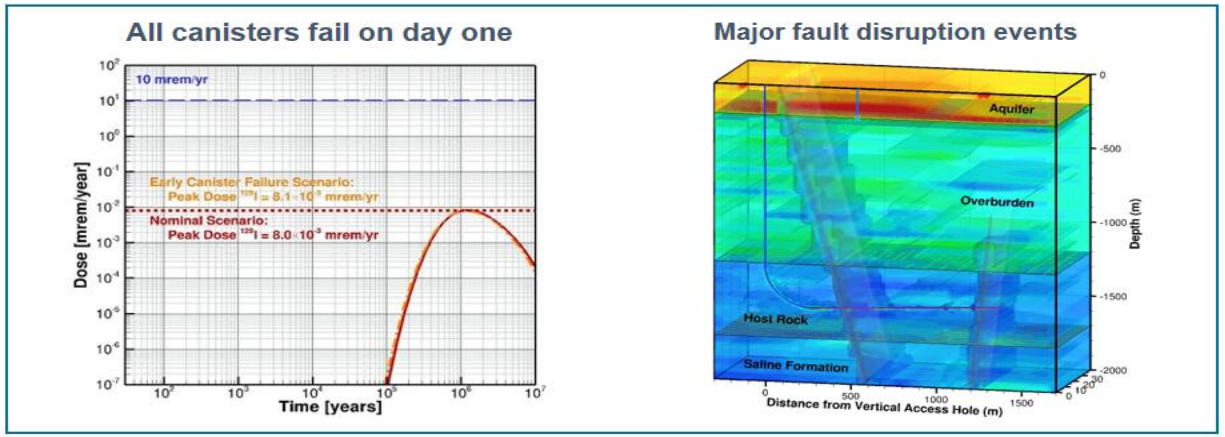
- Peer reviewed safety calculations support robust safety. Peak dose is 3 orders of magnitude below a 10mrem regulatory limit



SENSITIVITY ANALYSIS AND DISRUPTIVE SCENARIOS

- The baseline repository design is robust to uncertainty in model parameters
- The repository design is robust to extreme events, providing a margin of safety similar to the base case





An Equitable Solution

COMMUNITY EQUITABILITY

- We are committed to stakeholder partnership and consent
- Our research shows borehole disposal offers potential to address key community concerns about geologic disposal

GENERATIONAL EQUITABILITY

- Can be implemented in years, not the decades required for traditional repositories
- Helps our generation deal with our own legacy and newly-generated waste, rather than keep 'kicking the can down the road'

Our demonstration facility in Cameron, Texas

DEEP ISOLATION

An Affordable Solution

1

Lower costs across the repository lifecycle

Lower transport costs → Lower construction costs → Faster implementation → Avoided storage costs → Lower operational costs

Our published case studies show savings of 50-70%

2

Lower financial risk

- The bulk of costs for construction of a borehole repository are based on off-the shelf technologies that are deployed on a daily basis in the oil and gas sector
- Reduces the risk of cost and delivery overruns

UK case study

UK case study – purpose and objectives

- In February 2020, as part of UK Government's policy to explore alternative options for high activity waste disposal, NDA commissioned us to undertake a preliminary assessment of Deep Isolation's solution in the UK context
- The work is nearly finished, and will be published later this year
- No decisions have been made by NDA about our technology, but they are happy for us to share some of the preliminary conclusions from our work so far

PURPOSE

To provide NDA with information that enables it to assess the potential suitability of Deep Isolation's horizontal borehole disposal solution for elements of the UK's nuclear waste inventory

OBJECTIVES

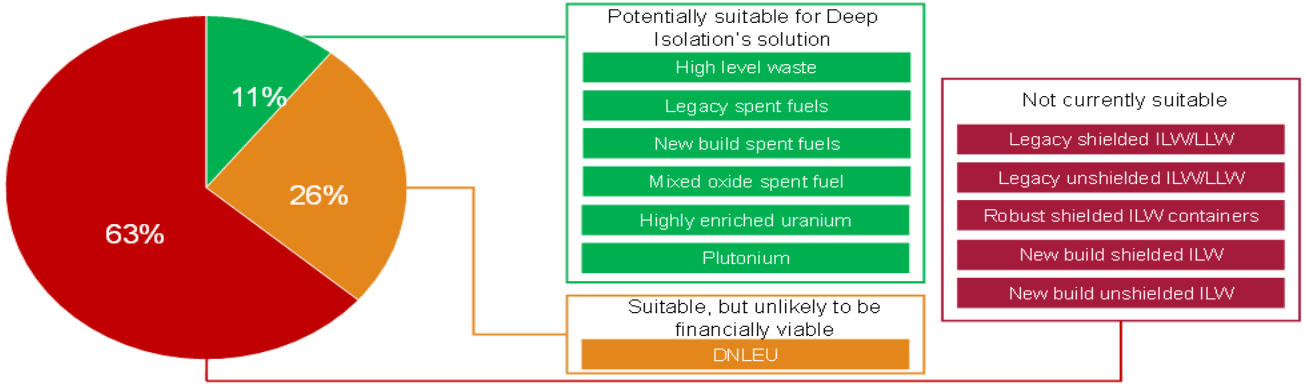
1. To map Deep Isolation's solution against the UK Inventory for Geological Disposal
2. To map our solution against three typical UK geologies
3. To describe and evaluate Deep Isolation's concept in the context of the UK's generic safety case for geological disposal
4. To prepare high-level cost estimates for use of our solution in the UK

UK case study – preliminary conclusions

1

11% of the UK's Inventory for Geological Disposal is potentially suitable for disposal in horizontal boreholes.

This includes all the UK's high heat generating waste



2

Deep Isolation's solution is aligned with safety expectations across the three generic UK geologies – but with further evidence and demonstration needed in Higher Strength Rocks

Components of the generic Disposal System Safety Case		Geological environments		
		LSSR	HSR	Evaporite
The Transport Safety Case	Transport Safety strategy, principles and approach			
	Safety of the transport package			
	Safety of the transport system			
The Operational Safety Case	Site selection and characterisation			
	Construction and non-radiological assessment	+	+	+
	Normal operations safety assessment			
	Accident safety assessment			
	Criticality safety assessment			
The Post-closure Environmental Safety Case	Safety concept			
	Maintenance of the engineered barrier system functions			
	Post-closure safety			
	Gas generation and migration			
	Natural events and climate change	+	+	+
	Site characterisation			
	Understanding of long-term evolution			
	Human intrusion	+	+	+
	Passive safety	+		+
	Multiple safety functions			

Key:
- Evidence suggests that Deep Isolation's solution is likely to be able to meet UK safety requirements.
- There is no reason to believe that Deep Isolation's solution could not meet UK safety requirements, but evidence for this has not yet been sufficiently documented.
- New research and analysis is needed to determine whether or not Deep Isolation's could meet UK safety requirements.
- Evidence suggests that Deep Isolation's solution is unlikely to be able to meet UK safety requirements.
- + Also offers potential additional safety benefits.

3

Cost estimates across 15 scenarios range from £1.92 - £2.65 billion for all HHGW

	Higher strength rock	Lower strength sedimentary	Evaporite
Use of one location for the disposal of all HHGW	Scenario 1	Scenario 2	Scenario 3
Use of two locations for the disposal of all HHGW	Scenario 4	Scenario 5	Scenario 6
Use of one location for the disposal of all legacy Spent Fuel	Scenario 7	Scenario 8	Scenario 9
Use of two locations for the disposal of all legacy Spent Fuel	Scenario 10	Scenario 11	Scenario 12
Disposal of all HLW in a single location	Scenario 13	Scenario 14	Scenario 15

Within that, ranges for HLW only are £0.33-0.36 billion, and legacy spent fuel are £0.69-£0.9 billion

4

Further work and analysis is needed on a range of regulatory, social, geological and operational issues

FINAL THOUGHTS

- The world has not yet disposed any of the spent fuel it has created over the last 70 years
- The current model for geological disposal is simply not scalable
- Directionally-drilled borehole repositories offer a feasible, scalable, safe and affordable solution - and the technology to deliver this exists now
- Deep Isolation is committed to working with you to make this happen

DEEP ISOLATION

Thank you

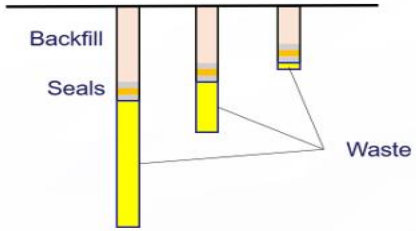
chris@deepisolation.net

Overview for IFNEC
5 November 2020

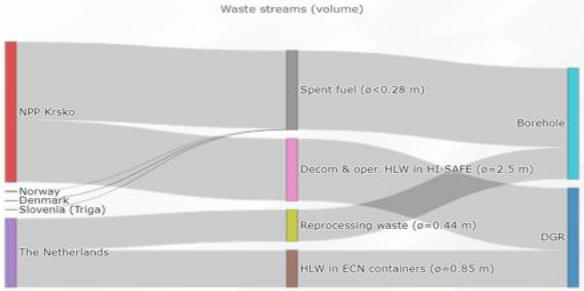
DEEP ISOLATION

The ERDO Borehole Disposal Project

Håvard Kristiansen
Norwegian Nuclear Decommissioning &
European Repository Development Organization



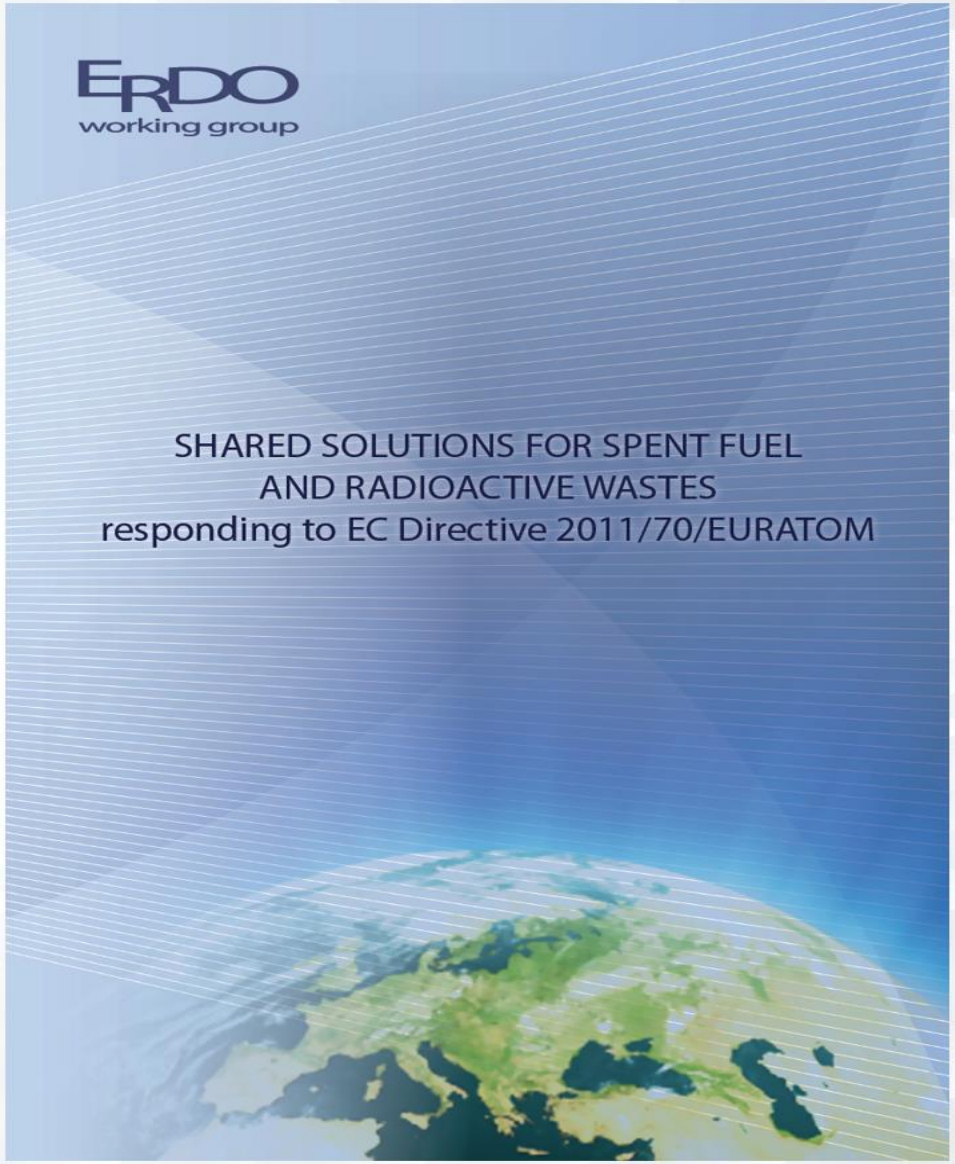
ERDO working group



NND

The European Repository Development Organization

- Consists of waste-management organizations from European nations with small inventories of radioactive waste.
- Originally formed as a working group for studying multinational repositories
- Now focuses more competence sharing, as well as on advancing knowledge about the potential of multinational repositories.
- Borehole disposal is of interest both as a topic for shared development and as a potential concept for a multinational repository



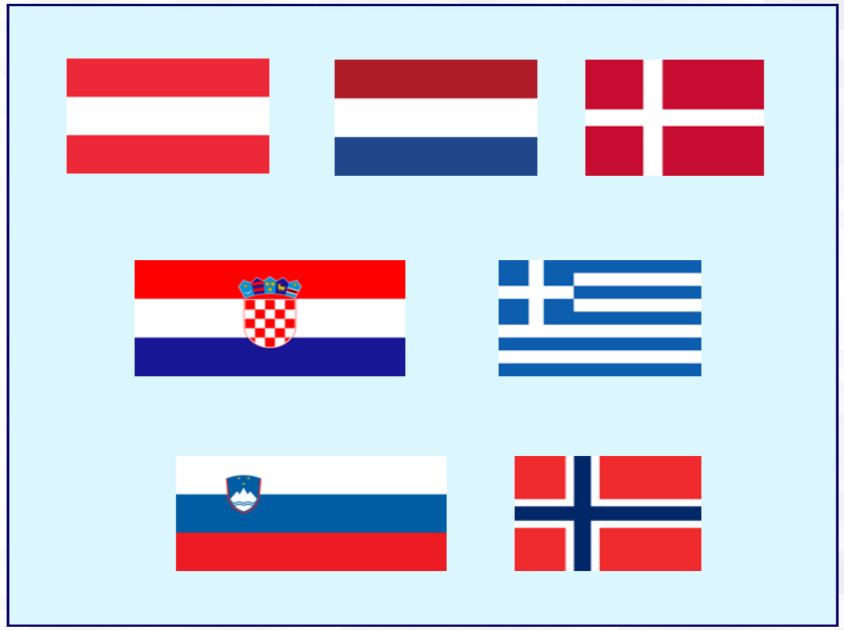
ERDO borehole project

Purpose of the project: To describe one or more specific borehole disposal concepts, based on available (drilling) technology and the anticipated waste inventory of participating nations.

Output (**this presentation contains the topics in bold**):

- **One or more reference designs for a borehole disposal facility**
- **Compatibility of national waste inventories with the reference design**
- **Cost estimates**
- **Strategic implications of borehole disposal**
- Assessment of project risk
- Strategy for developing a safety case
- Time of implementation
- RD&D-need

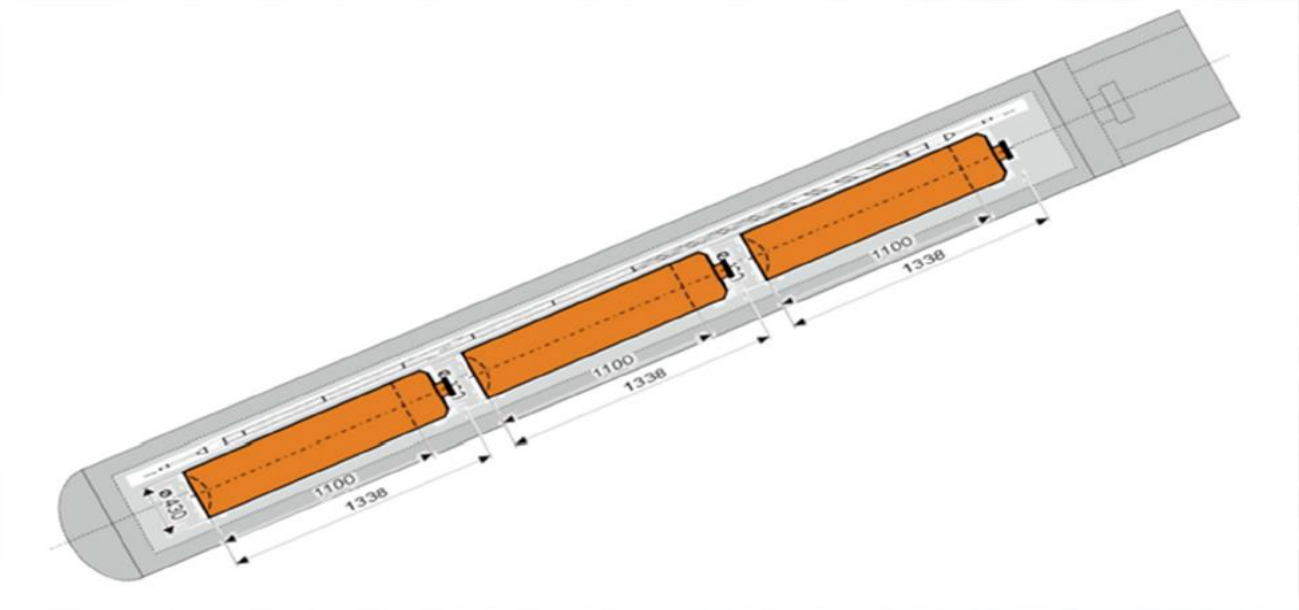
Start of project: Jan 2020. End: June 2021



NND

Our reference design includes a canister that is compatible with both spent fuel and HLW from reprocessing

- BSK-R container
  - external length: 5060 mm
  - internal length: 4845 mm
  - internal diameter: 431 mm
  - external diameter: 520 mm
- A specific design needs to be developed, including:
  - Copper coating with cast iron or steel insert?



DBC-R container, containing three canister of reprocessing waste and one fuel rod (Bracke et al.)

Bracke, G., Charlier, F., Liebscher, A., Schilling, F., Röckel, T. (2017): About the Possibility of Disposal
of HLRW in Deep Boreholes in Germany. - Geosciences, 7, 3.

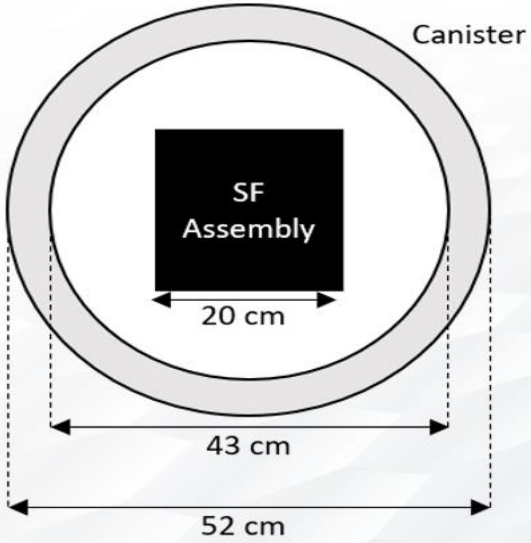
NND

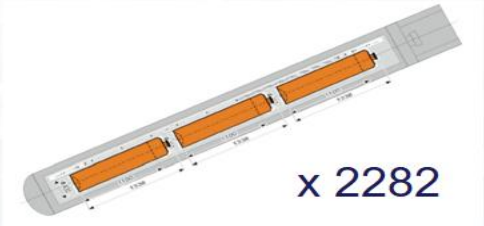
Croatia and Slovenia

- Share ownership and responsibility for the nuclear powerplant in Krško
- 2282 assemblies (926 tons) of spent fuel expected by final shut down
- Slovenia will also need to manage approximately 0.2 tons spent fuel from a Triga research reactor, which is expected to remain in operation until 2043. For simplicity, the Triga fuel is not included in the following analysis
- 1 fuel assembly per borehole canister gives 2282 canisters
- Narrower canisters (lower cost for the same borehole length) or wider canisters (>1 assembly per canister) should be considered

Decommissioning and operation of an encapsulation facility for spent fuel is expected to generate 409 m^3 HLW, packed in HI-SAFE-containers (diameter = 2.5 m, too large for boreholes)

Photo: Slovenia Times

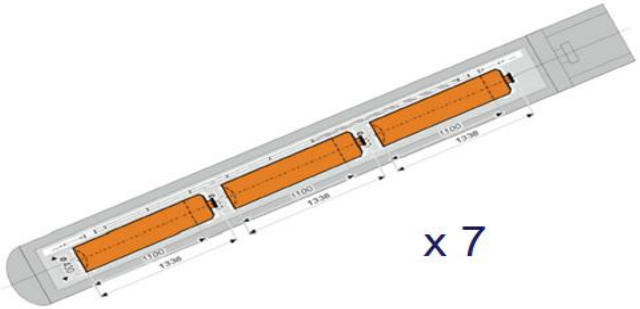




NND

Denmark

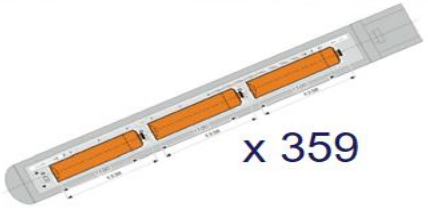
- Denmark has had three research reactors in operation. All have been shut down.
- The fuel has been returned to the country of origin, but 233 kg of residues from post-irradiation experiments remain. This is classified as high-level waste (but it is not heat generating)
- The 233 kg are held in 33 stainless steel cylinders, 5 of which could fit in each borehole canisters. Therefore, Denmark would need 7 borehole canisters.



x 7

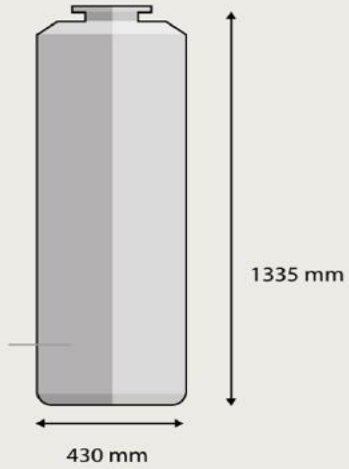
The Netherlands

- Nuclear power plants:
  - Borsele (1973-)
  - Dodewaard (1969-1997)
- Research reactors:
  - High-flux reactor (1961-)
  - Low-flux reactor (1960-2010)
  - Hoger Onderwijs Reactor (1963-)
- The Dutch strategy is to accumulate and store waste until 2130, while investigating permanent solutions

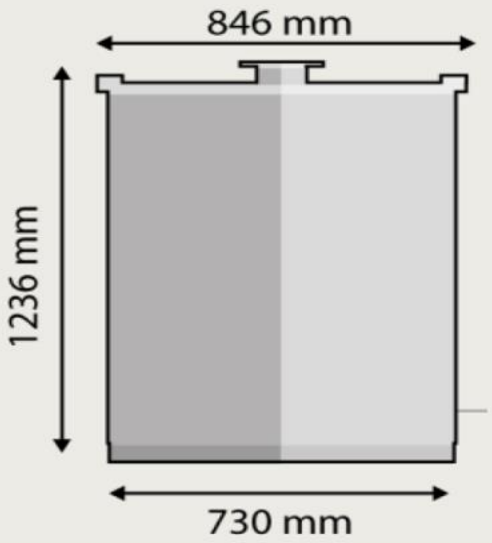


Expected inventory in 2130

1078 canisters of reprocessing waste (CSD-V and CSD-C). These could fit in 359 borehole canisters



350 ECN-containers of spent research reactor fuel and other HLW. ECN-containers are too wide for the reference borehole

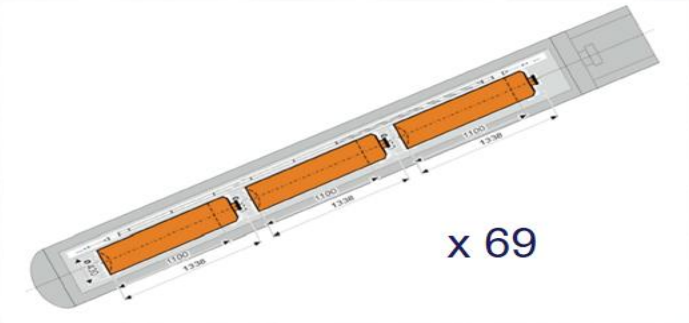


Figures: COVRA

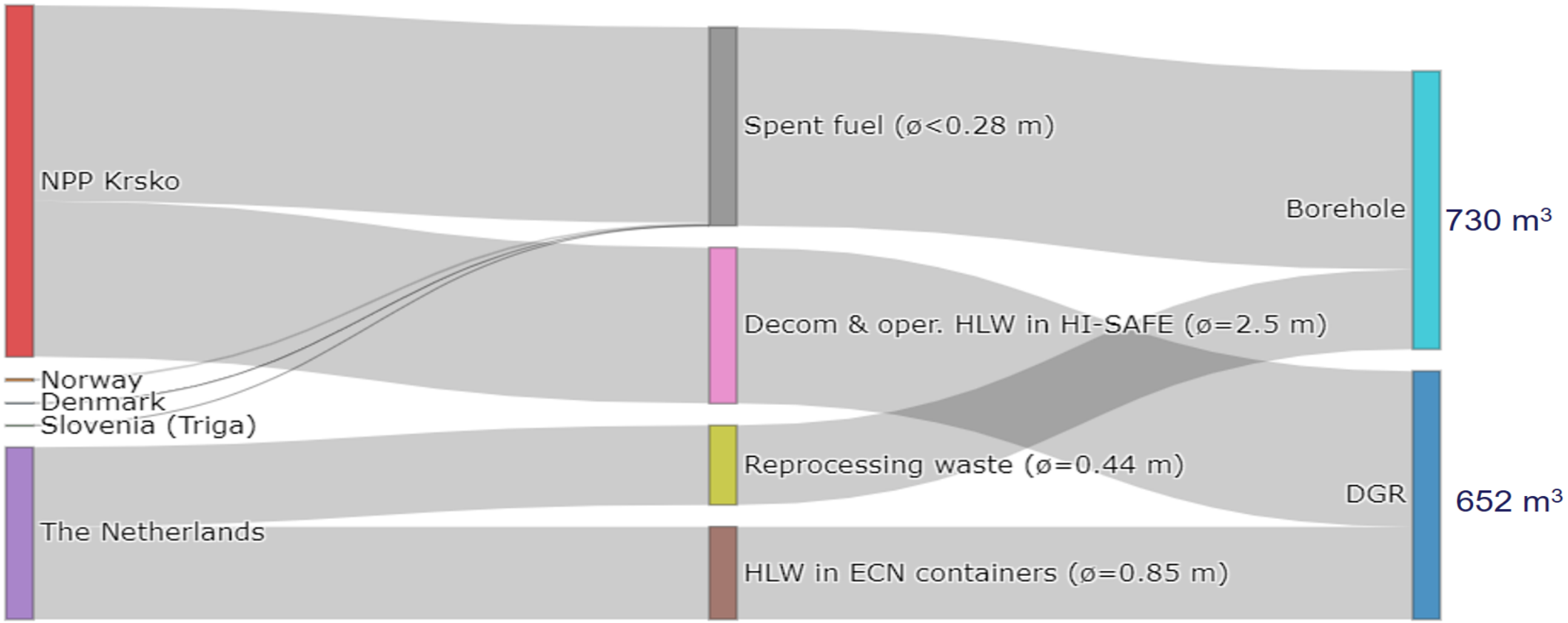
Norway

- Norway has had four research reactors in operation. All are now shut down.
  - Joint Establishment Experimental Pile I (JEEP I)
  - Norwegian 0-energy Reactor Assembly (N0RA)
  - JEEP II
  - Halden Boiling Water Reactor
- 16.5 tons of spent fuel of various types require a long-term solution. It could all fit in 69 borehole canisters.

JEEP II (Photo: IFE)



A significant portion of, but not all the waste could fit in the borehole concept



Shallow (little or no overburden) formations with low-permeability, competent and drillable host rock enable relatively shallow disposal.

Uncertainties in safety requirements (e.g. canister lifetime and spacing) → design uncertainties → cost estimate uncertainties

Time-dependent radiotoxicity, waste-form stability, and the mobility of radionuclides depends on the waste. These factors affect the safety requirements, such as depth and canister properties.

Costs 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

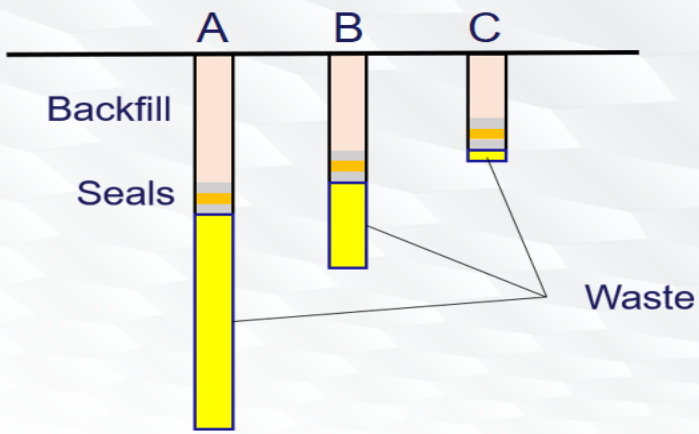
The cost of a borehole **increases exponentially with depth**.

Wider holes can accommodate larger waste packages and therefore potentially more waste per unit depth.

Wider holes are more expensive than narrower holes, because they need bigger rigs for casing strings etc.

NND

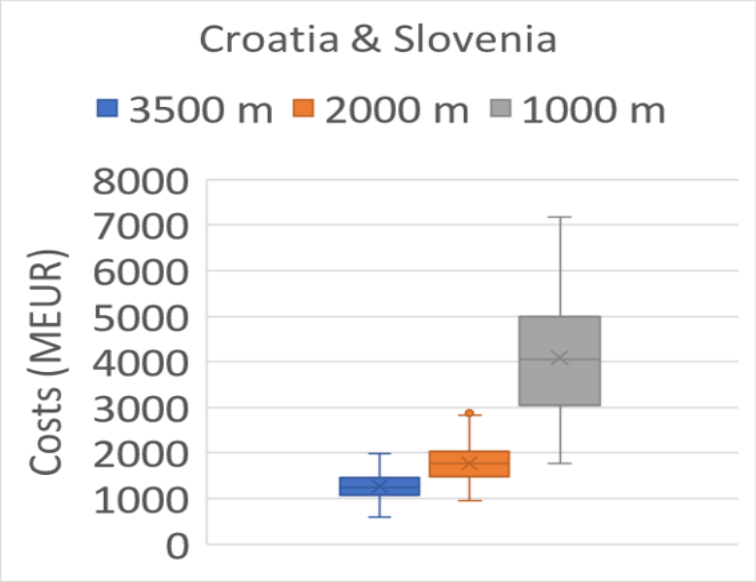
The following slides show the results of a Monte Carlo simulation with three concepts and three variables, carried out for each national inventory (Croatia and Slovenia combined)



	
Croatia & Slovenia	2282
Denmark	7
Netherlands	359
Norway	69

		A	B	C
Fixed parameters	Total borehole length (m)	3500	2000	1000
	Length of disposal zone (m)	2000	800	100
	Length of sealing and backfilling zone (m)	1500	1200	900
Variables	Cost of site investigation + construction + sealing (MEUR)	60-120	40-80	10-30
	Buffer distance between canisters in the disposal zone (m)	0.4-4.4		
	Operational/emplacement cost per canister (MEUR)	0.03-0.3		

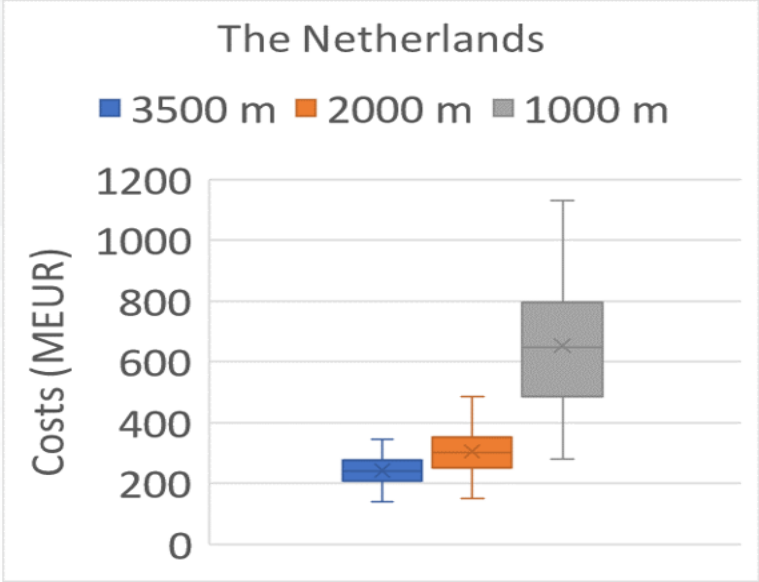
Parameters and ranges of variables estimated based on available literature

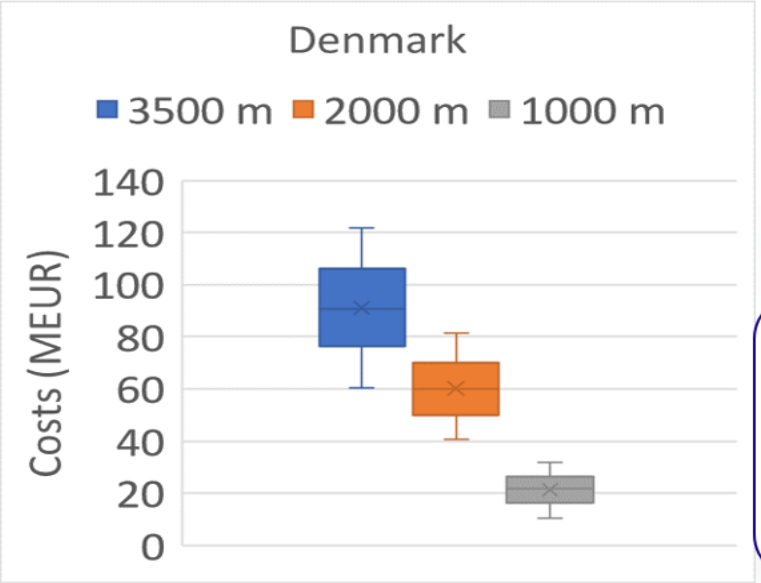


Borehole disposal designs must be tailored to each individual situation to identify an optimal design that yields the least cost.

Economies of scale favour large boreholes for larger inventories

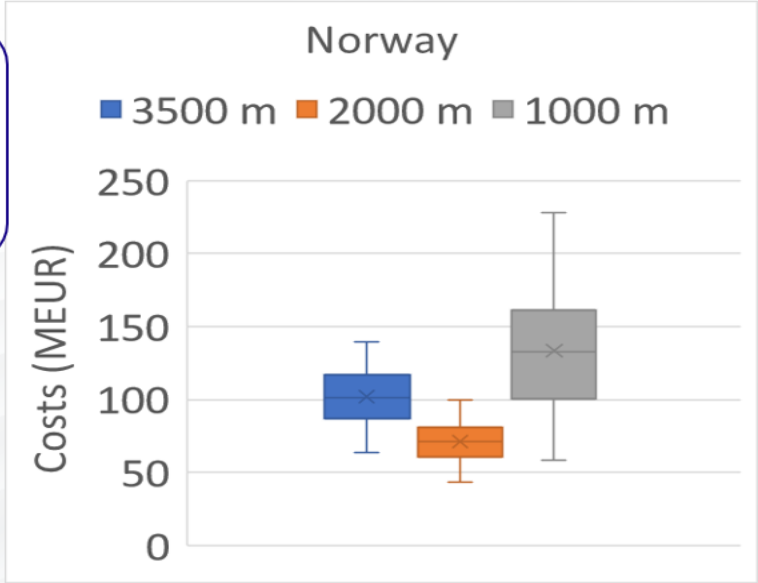
Significant cost reductions are probable for Croatian and Slovenian waste if the design is adapted to the size of the fuel assemblies





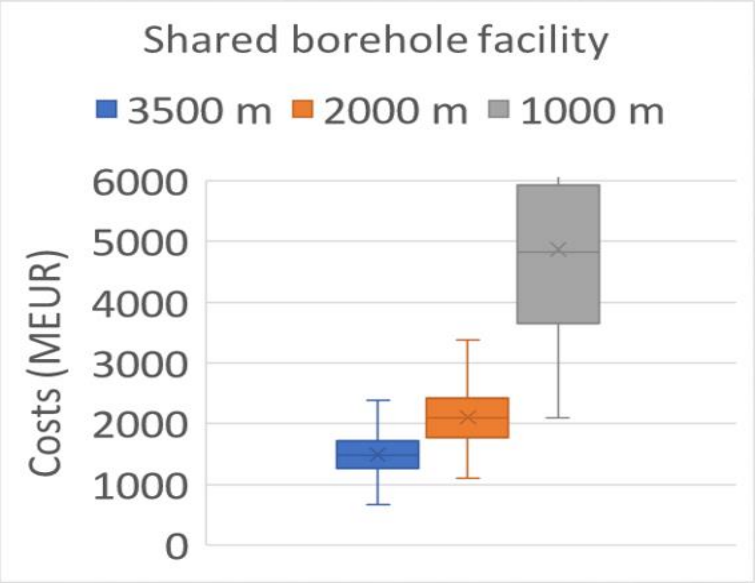
Norway would need 5-7 boreholes of 1000 m depth, but no more than one 2000 m deep one. The latter is therefore more cost efficient.

Denmark needs only one short borehole, but geological conditions and safety assessments could make the 2000 m deep design necessary.



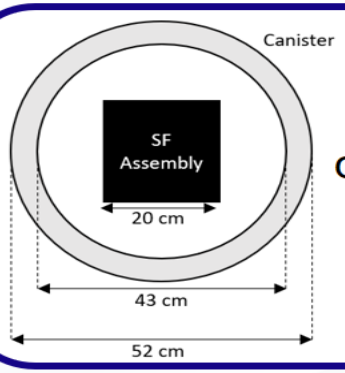
Borehole disposal challenges the rationale of multinational repositories

	Median cost of the most cost-efficient concept (MEUR)
Croatia & Slovenia	1241
Denmark	21
NL	240
+ Norway	71
= Sum	1573
Shared facility	1474
Savings from sharing (%)	6 %

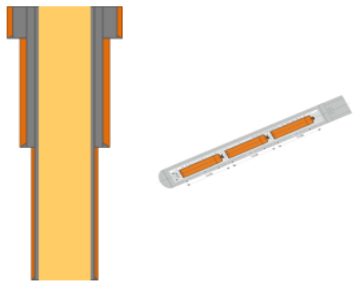


The modular nature of borehole disposal could enable small-inventory states to independently implement a permanent solution to their high-level radioactive waste at a relatively low cost.

	Inventory size	Cost	**Unit cost**	Comment
Netherlands	209 m^3	238 MEUR	**1.1 MEUR/m^3**	**0.6 m** wide, 3500 m deep diameter borehole
Croatia & Slovenia	926 tons	1226 MEUR	**1.3 MEUR/ton**	
Sandia NL (Arnold, 2011)	254 tons/borehole	40 MUSD/BH	**0.16 MUSD/ton**	**0.34 m** diameter 5000 m deep borehole.
Bates (2015)	80 000 tons	4000-15 200 MUSD	**0.05-0.19 MUSD/ton**	**0.41 m** diameter, 2000-2700 m deep boreholes
Deep Isolation (2020)	2000 tons	724 MUSD	**0.36 MUSD/ton**	**0.44 m** diameter horizontal drillholes
Deep Isolation (2020)	151 800 tons	82 000 MUSD	**0.54 MUSD/ton**	
SKB PASS-project: Deep boreholes (1992)	7757 tons	7490 MEUR	**0.97 MEUR/ton**	Recalculated to 2020-costs
France (Cigeo, 2012)	85 000 m^3	34 400 MEUR	**0.40 MEUR/m^3**	Mined repository
Finland (Posiva, 2012)	5486 tons	3500 MEUR	**0.64 MEUR/ton**	Mined repository



Optimization of the canister design could reduce the costs significantly for Croatia & Slovenia

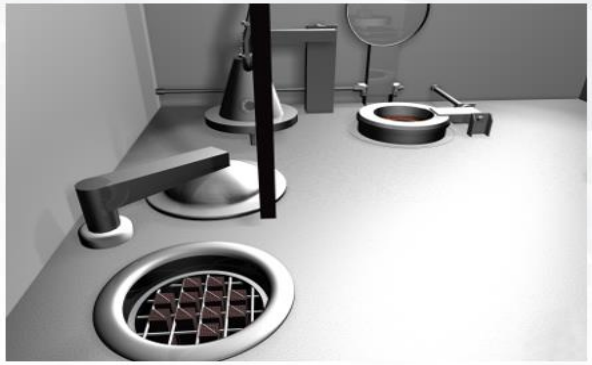


Our reference design is robust and applicable for all project members, but it is not necessarily the optimal design for all.

Encapsulation remains an unanswered question

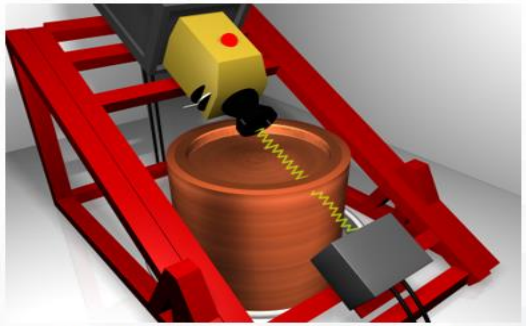
Filling and sealing canisters could require advanced and costly facilities, **but requirements and costs depend on the safety functions of the canisters.**

Posiva's encapsulation facility

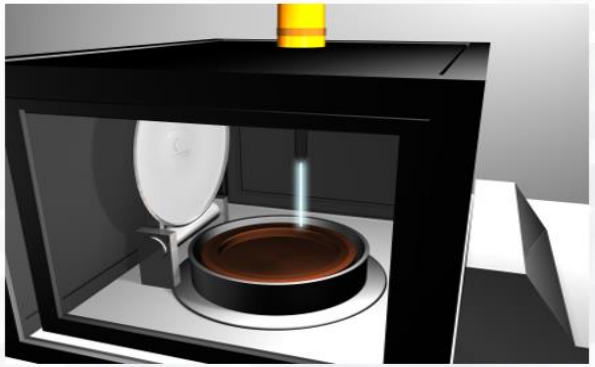


Waste transfer

Encapsulation, R&D, tools, procedures, and competence could be topics for international collaboration or commercial enterprise.



Inspection of welded joint, using x-rays



Electron beam welding

All images from Posiva Oy (http://www.posiva.fi/en/final_disposal/final_disposal_facility/encapsulation_plant)

Take-home messages

Costs 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.

The modular nature of borehole disposal could enable small-inventory states to independently implement a permanent solution to their high-level radioactive waste at a relatively low cost.

Borehole disposal designs must be tailored to each individual situation to identify an optimal design that yields the least cost.

Encapsulation, R&D, tools, procedures, and competence could be topics for international collaboration or commercial enterprise.

Thank you for your attention.

havard.kristiansen@nnd.no

NND

CSIRO

Australian Government

ANSTO
Science. Ingenuity. Sustainability.

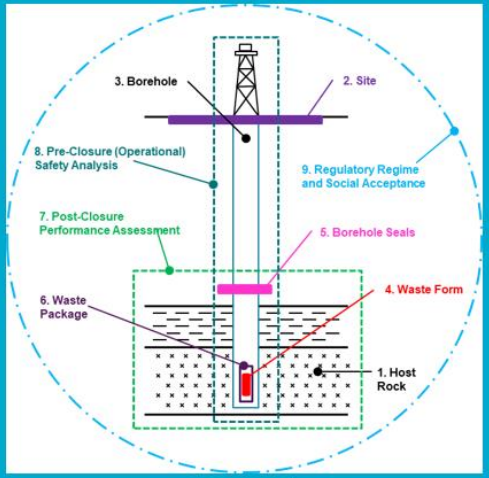
Sandia National Laboratories

Borehole Disposal Demonstration Project: Overview & Collaboration Opportunities

Presentation to IFNEC

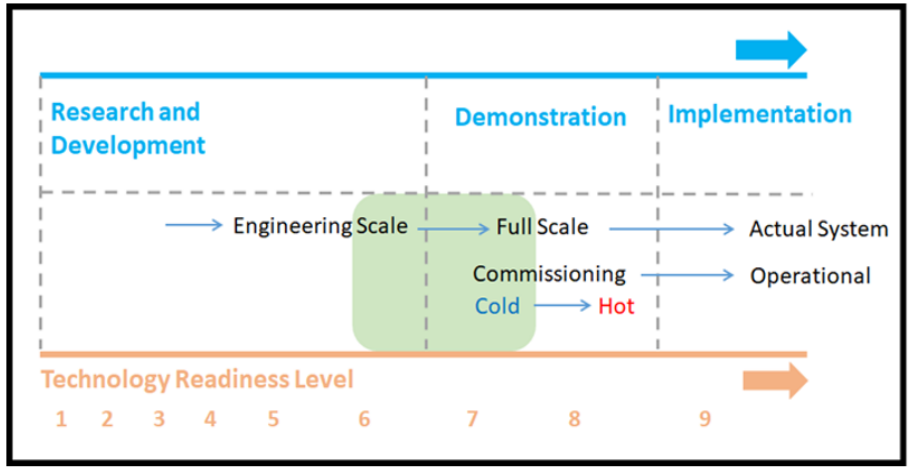
Dirk Mallants, Tito Bonano, Geoff Freeze, Patrick Brady, David Sassani | 5/11/2020

Australia's National Science Agency



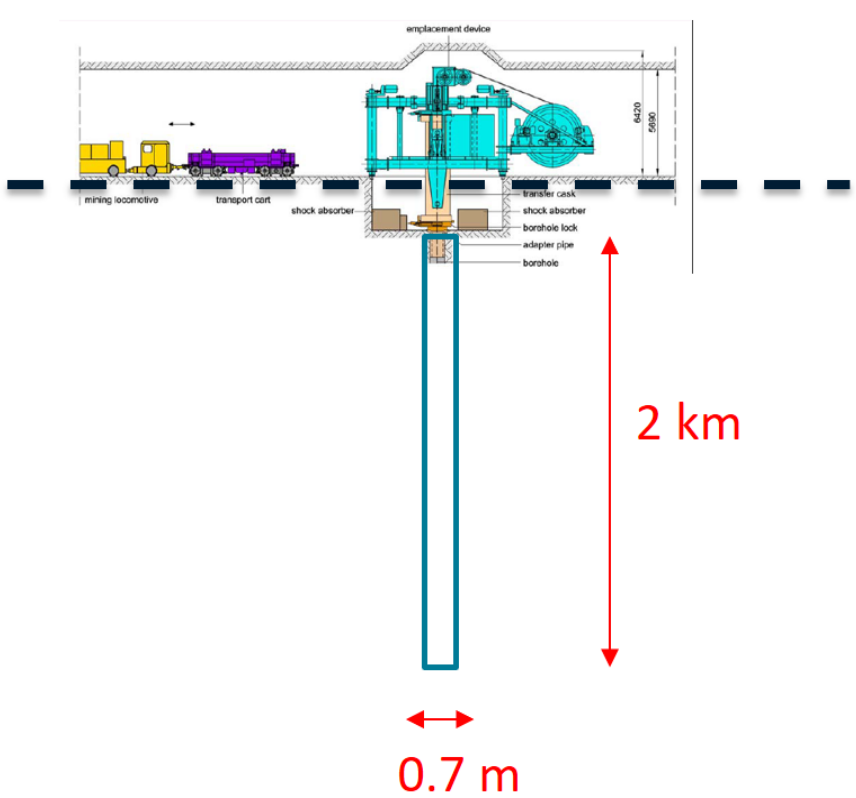
Borehole disposal: Technical feasibility and conditions for long-term safety

- Deep Borehole Demonstration Project
  - ✓ Near surface waste emplacement testing
  - ✓ Development of wasteforms & disposal containers
  - ✓ Development of enabling technologies
  - ✓ Waste emplacement testing in a deep, large-diameter borehole

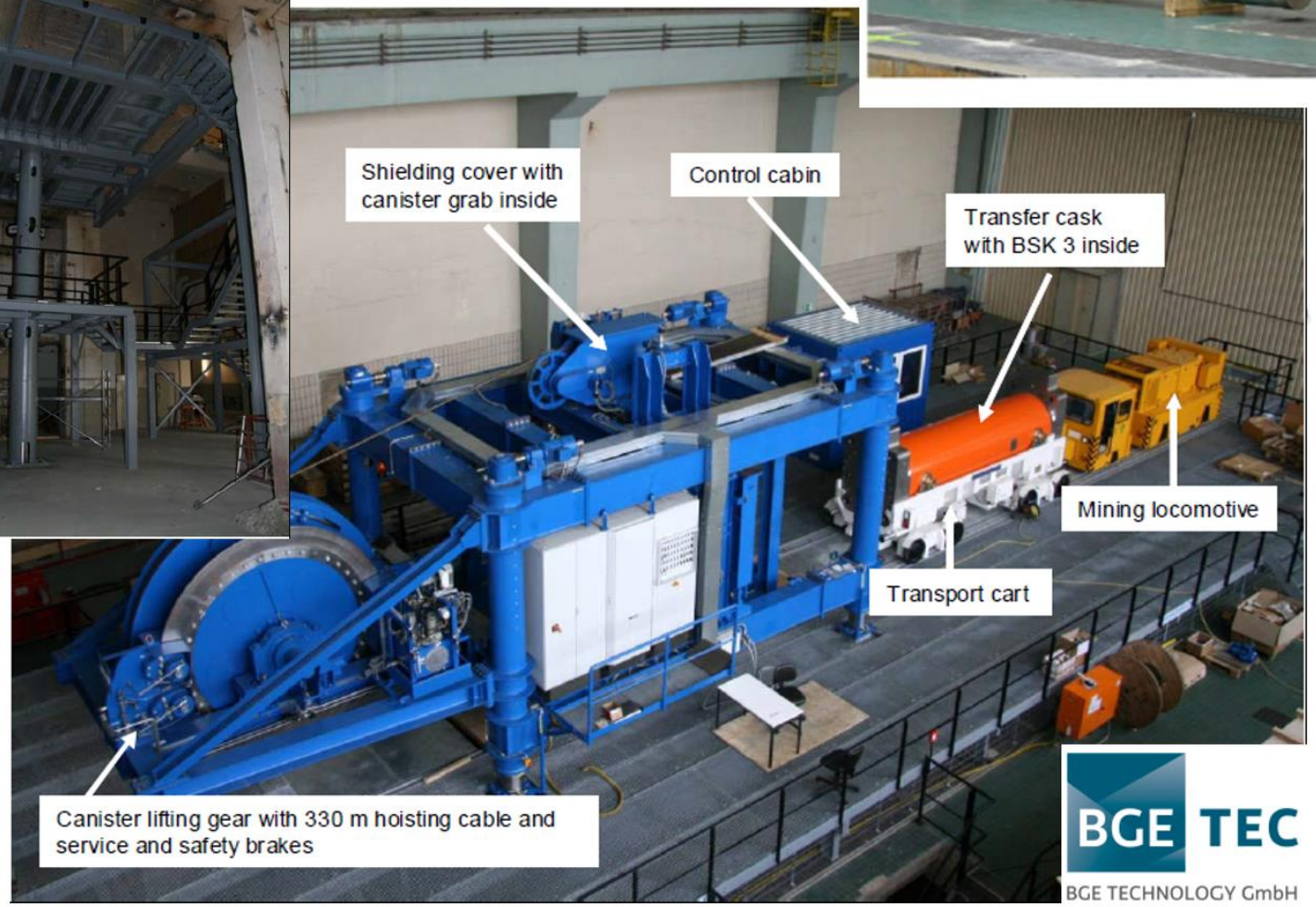


Waste emplacement tests

- Above-ground tests
  - ✓ Container unloading & emplacement
- Below-ground tests
  - ✓ Deep drilling
  - ✓ Rock sensing
  - ✓ Container emplacement



Waste emplacement tests



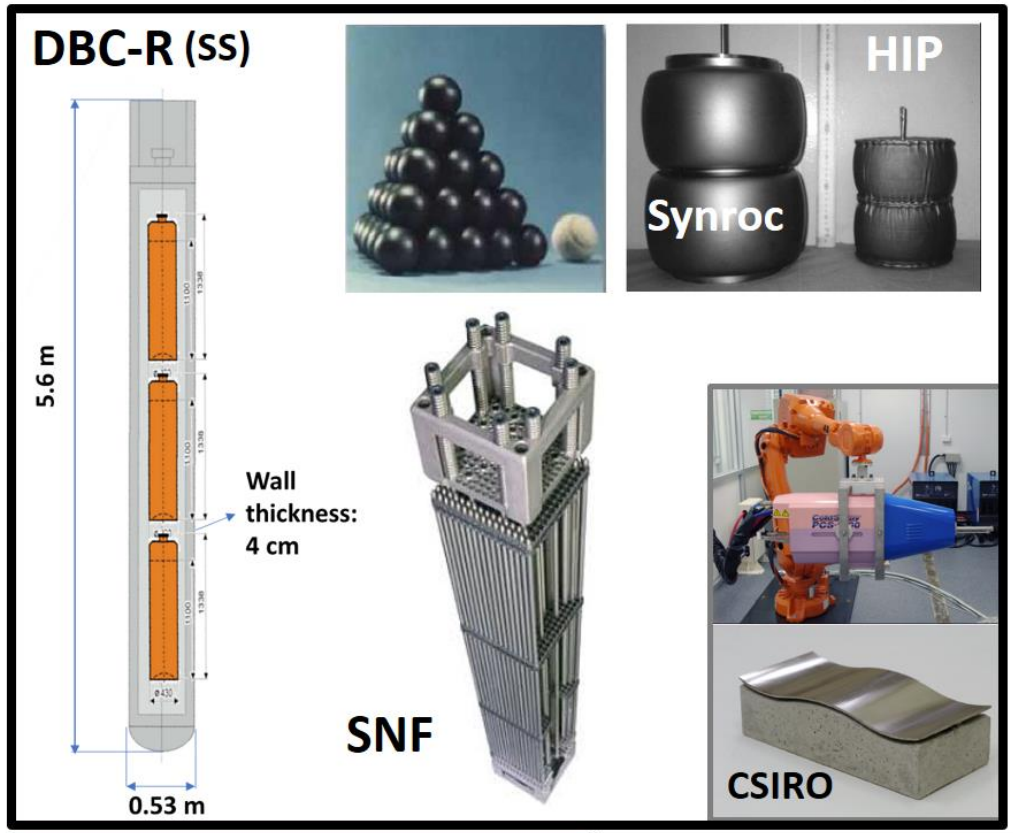
BGE TEC
BGE TECHNOLOGY GmbH

Novel wasteforms & disposal containers

Australian Government

ANSTO
Science. Ingenuity. Sustainability.

- Synroc wasteform
  - ✓LEU from Mo-99
  - ✓Pu immobilisation
  - ✓Gen(IV) wastes
  - ✓SMR wastes
- ✓ Wasteform alterations under borehole environment
- ✓Multi-purpose disposal container

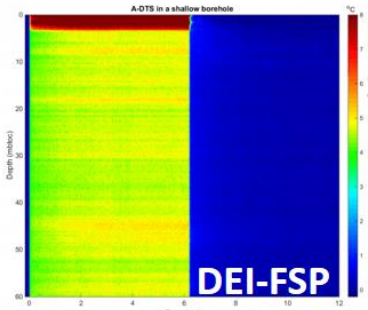


Container design: Bracke et al. 2016, 2017, 2020

Metallic coating (Cu, Ti): Cold spray

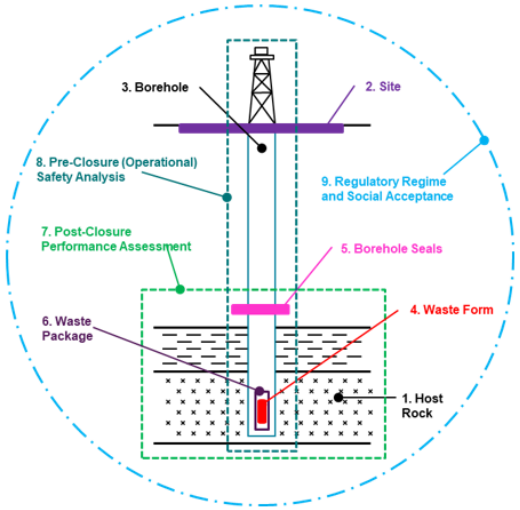
Enabling technologies

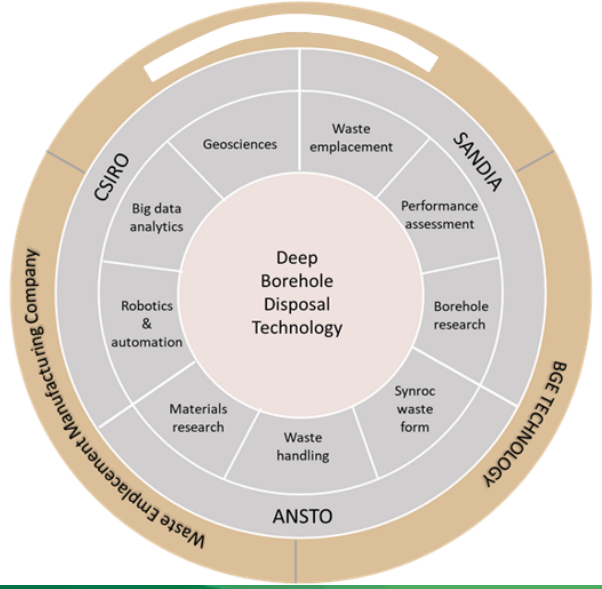
- Borehole sealing materials
  - ✓Bentonite under extreme conditions (TMC)
- Advanced sensing
  - ✓Rock features at great depth
- Robotics
  - ✓Waste handling during emplacement
- Monitoring
  - ✓Seal performance: fiber optics, wireless sensing
- Siting
  - ✓ML for unbiased site screening



Waste emplacement in deep, large-diameter borehole

- Full-scale demonstration tests
  - Characterisation borehole (2000 m)
  - Drilling deep, large-diameter hole (2000 m)
  - Waste emplacement testing of dummy canister & seal emplacement
- Performance and Safety Assessment
  - Various waste types/forms
  - Various scenarios
  - Safety case
- Timescale: 2021-2028
- Multi-organisation collaboration (Borehole Demonstration Consortium)



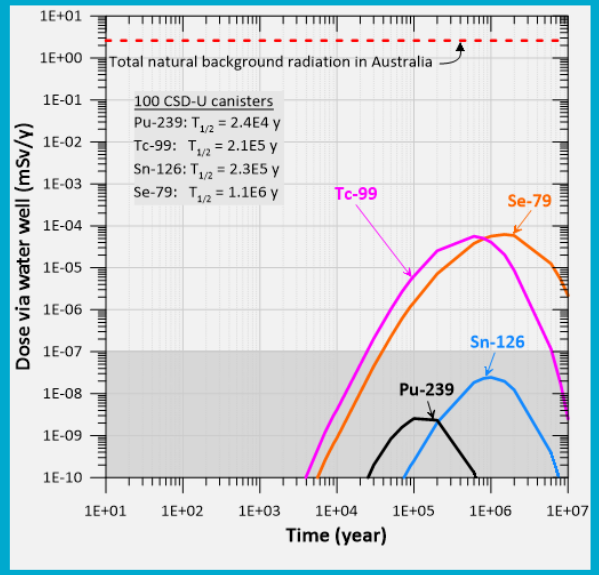


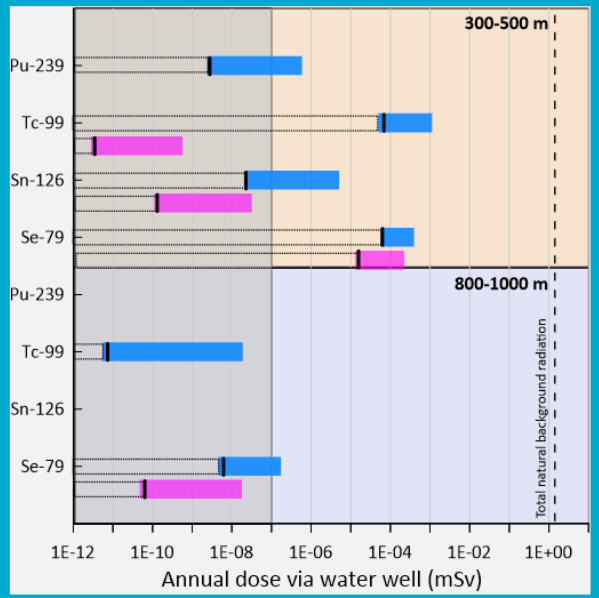
CSIRO

Generic safety assessments

Model set-up:

- Inventory: 100 CSD-U containers
- Disposal depths:
  - 300 – 500 m; 800 – 1000 m; 2800 – 3000 m
- Groundwater flow:
  - 0-25 m: Regolith (High permeability)
  - 25-100 m: Weathered basement rock (Medium perm)
  - > 100 m: Crystalline basement rock (Low perm)
- Sensitivity analysis for rock permeability:
  - Low perm x 100; Low perm/100
- Sensitivity analysis for radionuclide sorption
  - **Lower limit** – Upper limit sorption parameter
- Wasteform and engineered barriers:
  - Instantaneous release
  - No engineered barriers at disposal zone
  - Cementitious and bentonite seals above disposal zone





Confirm rocks devoid of fresh groundwater: Noble gases in fluids & fluid inclusions

Helium: ^{3}He, ^{4}He

Neon: ^{20}Ne, ^{21}Ne, ^{22}Ne

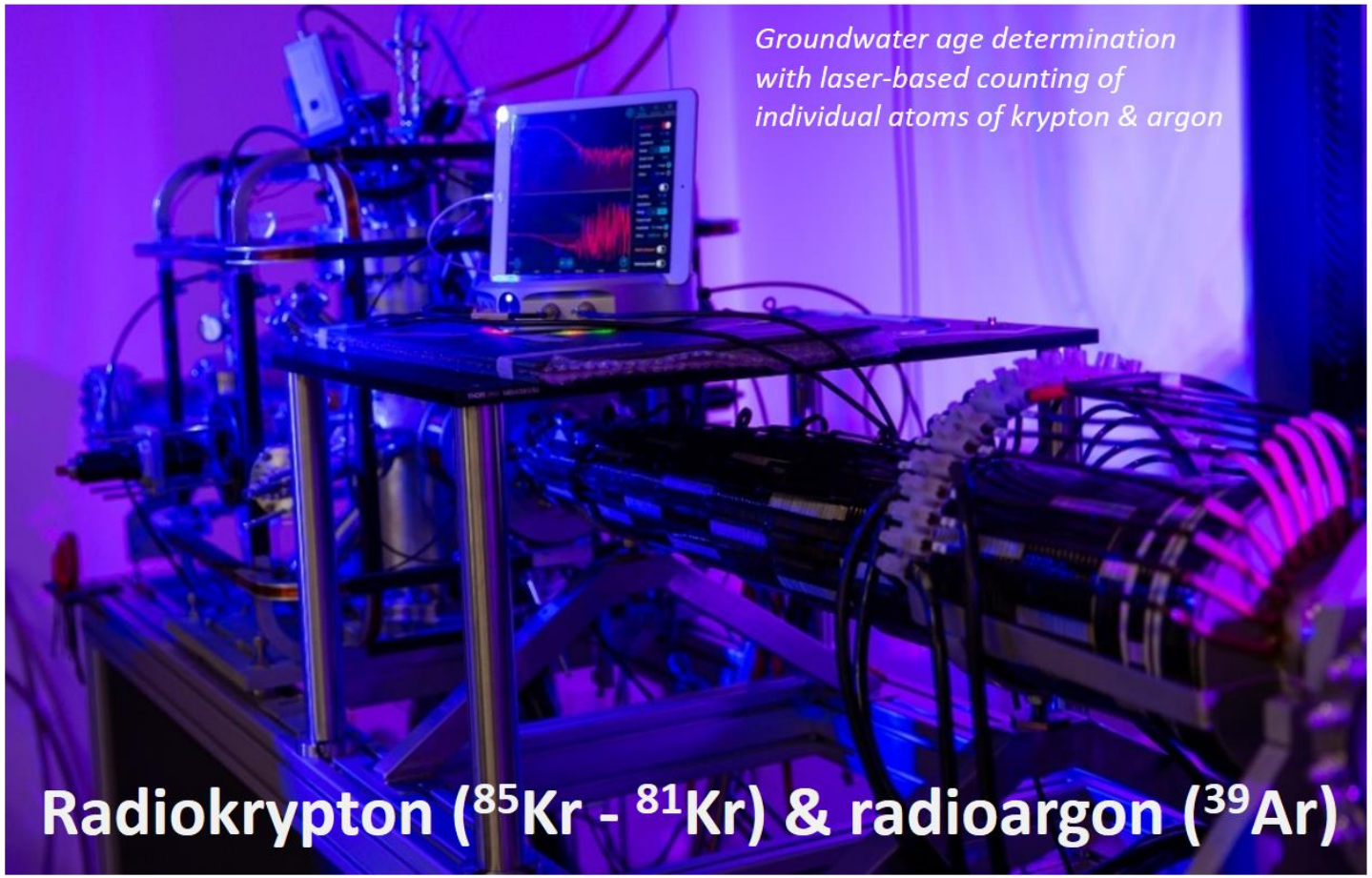
Argon: ^{36}Ar, ^{38}Ar, ^{40}Ar,

Krypton: ^{82}Kr, ^{83}Kr, ^{84}Kr, ^{86}Kr,

Xenon: ^{124}Xe, ^{126}Xe, ^{128}Xe, ^{129}Xe, ^{132}Xe, ^{130}Xe, ^{131}Xe, ^{134}Xe, ^{136}Xe

8 | Australia's National Science Agency

Atom Trap Trace Analysis - ATTA



Take home messages

- Many of the key components/technologies for demonstrating deep borehole disposal feasibility are available or need some, but limited modification.
- A full-scale, integrated drilling, waste emplacement and sealing test has not yet been undertaken, but is achievable in a 7-10 y timeframe
- International experience and collaboration should lessen the technical challenges
- Scientific and technological spin-offs (in-situ mining, seals for oil & gas, …)

Thank you

Land and Water
Dr. Dirk Mallants
Team Leader Environmental Tracers

+61 8 8303 8595
dirk.mallants@csiro.au
csiro.au/landandwater

Australia's National Science Agency

Some questions for the panel…

1. Are the safety case and the safety case requirements for DBD fundamentally different to a DGR and, if so, how do we communicate this?
2. What will it take to bring DBD up to a similar cycle and level of regulatory approval as ‘conventional' DGRs?
3. Where is the main technical challenge in building the credibility of DBD to a similar level as DGRs?
4. What are the key factors that a DBD demonstration test should address: are any of them in conflict (e.g., sealing v. retrievability)?
5. Is it correct that DBD opens up a much wider range of siting options than a conventional DGR?
6. How much site characterisation is actually necessary for DBD, compared to a conventional DGR and is it more or less demanding?
7. What type of national RWM programme do you consider the most likely users of a DBD facility and would it be integral to or separate from their main programme?
8. Where do you think we will be with DBD in ten years time - is it a solution worth investing in and waiting for?