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Geological disposal of radioactive waste

Technology & Evolution

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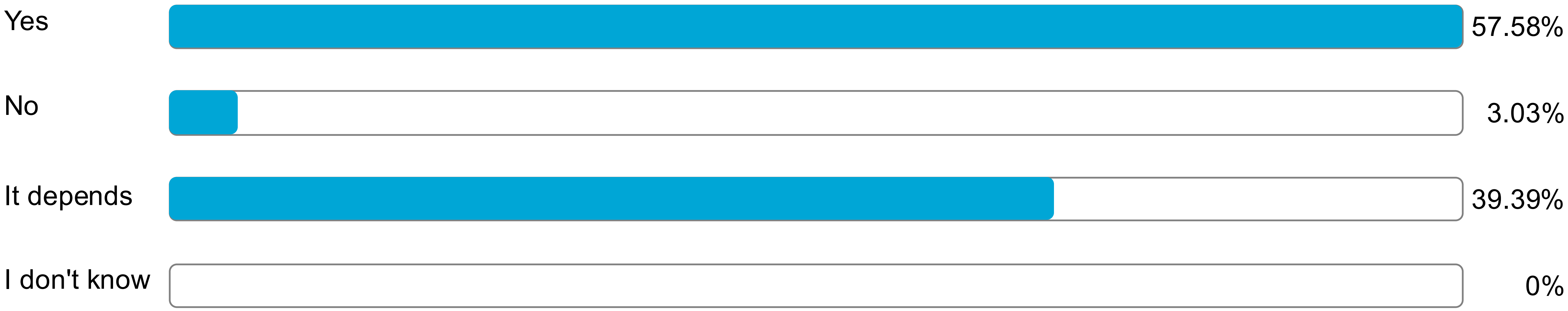
TU Delft
eurad 2 European Partnership on Radioactive Waste Management
NWO

Can nuclear energy play a role in the transition to net zero and long-term environmental sustainability?

Yes	0%
No	0%
It depends	0%
I don't know	0%

Can nuclear energy play a role in the transition to net zero and long-term environmental sustainability?



RESULTS SLIDE

What the EU Taxonomy says about this…

- CO_2 emissions from nuclear power plants over their life-cycle are comparable to those from renewable energy sources

  → Nuclear is a low-carbon energy source

- Compliance with the safety standards and waste management requirements ensures a high level of protection for the environment and for people
- For nuclear energy to be listed under the taxonomy:
  - Disposal facilities for low-level waste must be operational by 2050
  - Member States should have in place a detailed plan to have in operation a disposal facility for high-level radioactive waste by 2050

Reference: https://ec.europa.eu/commission/presscorner/api/files/document/print/en/qanda_22_712/QANDA_22_712_EN.pdf

Learning objectives

This lecture focuses on the geological disposal of radioactive waste.

By the end of this lecture, you should be able to:

- Understand the broad context of radioactive waste management, with a focus on high-level radioactive waste
- Describe the general concepts of geological disposal, including repository layout, the multi-barrier system, and the main phases and processes
- Demonstrate how research in geomechanics can be leveraged to ensure the safety and optimise geological disposal facilities for radioactive waste

Outline

1. General context of radioactive waste management
2. General concepts of geological facilities for radioactive waste disposal
3. Multiphysics processes
4. Geomechanical challenges:
   - Excavation Damaged Zone and clay host formation – support interaction
   - Buffer, seal and backfill behaviour
   - Temperature effects
   - Gas transport
5. Conclusions

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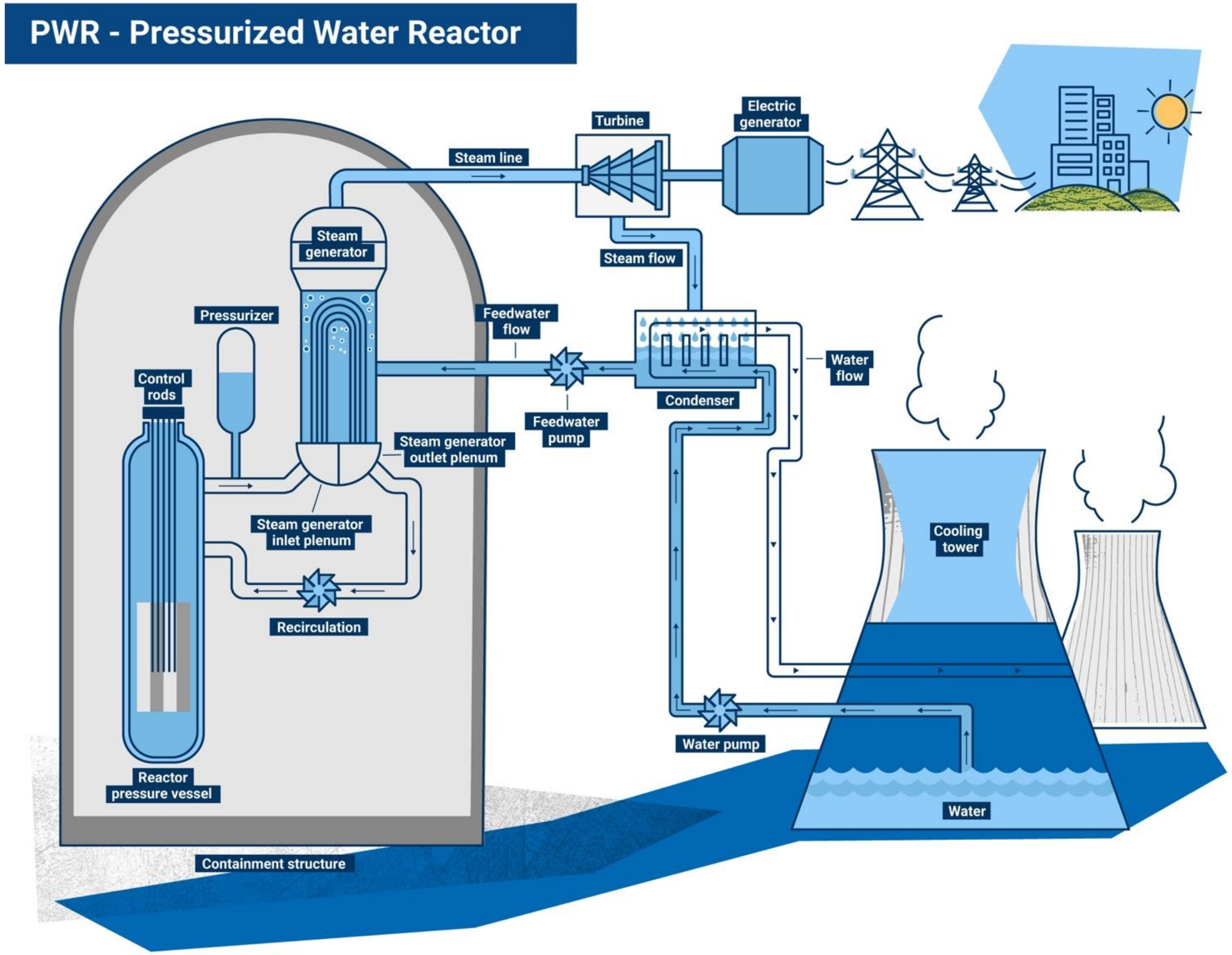
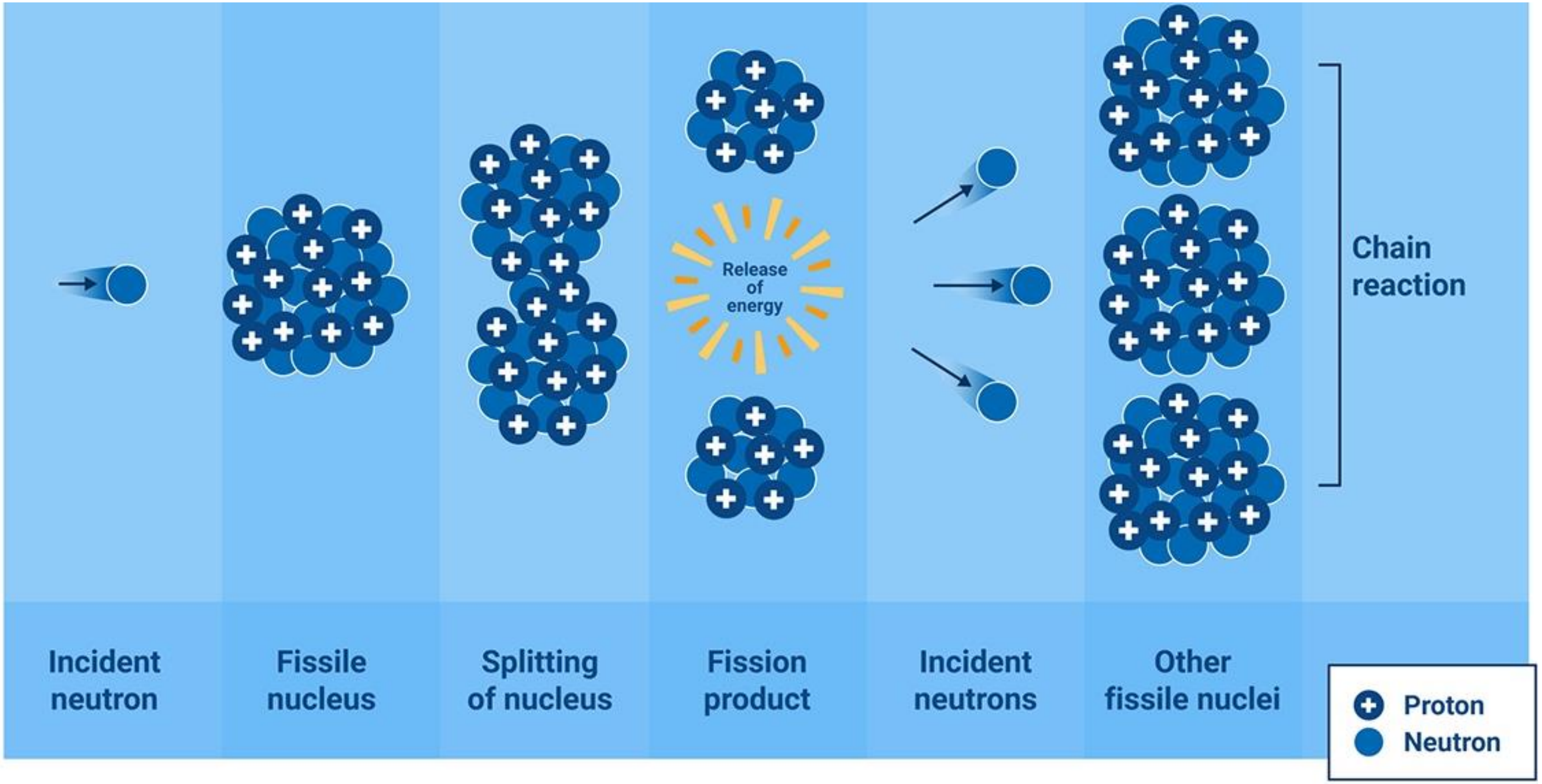
Nuclear reactor: principles



(https://www.iaea.org/newscenter/news/what-is-nuclear-energy-the-science-of-nuclear-power)

Nuclear reactor: fission



(https://www.iaea.org/newscenter/news/what-is-nuclear-energy-the-science-of-nuclear-power)

Nuclear reactor: energy production

- The fission of 1 atom of ^{235}U releases ~ 200 MeV, or 3.2×10^{-11} J inside the reactor
- This corresponds to ~ 82 TJ/kg
- By volume, uranium is
  - 33,000 times more energy dense than oil
  - 37,000,000 times more energy dense than natural gas
  - 43,000 times more energy dense than coal

Reference: https://world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/physics-of-nuclear-energy

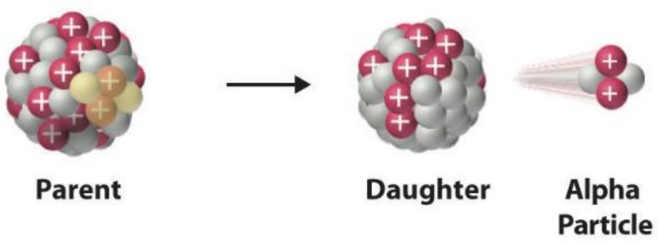
Nuclear reactor: fission products

Radioelement	1 Tonne U
Total uranium	955,4 kg
U-238	940,6
U-235	10,3
U-236	4,4
U-234	0,2
Total plutonium	9,74 kg
Pu-238	0,18
Pu-239	5,67
Pu-240	2,21
Pu-241	1,19
PU-242	0,49
Total minor actinides	0,776 kg
Neptunium-237	0,43
Americium-241	0,22
Americium-242	0,0007
Americium-243	0,10
Curium-242	0,00013
Curium-243	0,00032
Curium-244	0,024
Total Fission products	34,1 kg
Short & intermediate-lived FPs	31,1
Long-lived FPs, of which	3,0 including
Technetium-99	0,81
Iodine-129	0,17
Caesium-135	1,31
Zirconium-93	0,71

(https://radioactivity.eu.com/articles/radioactive_waste/spent_fuel_composition)

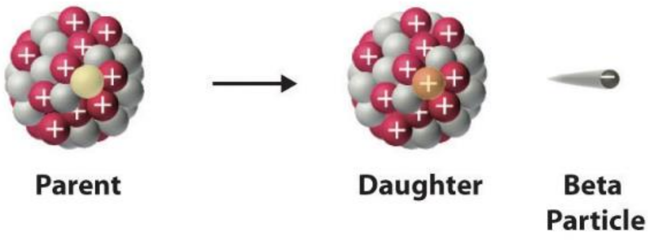
Radioactive waste: characteristics

Alpha decay



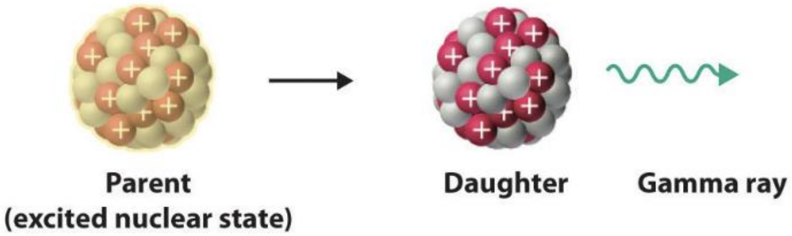
α are stopped by a sheet of paper

Beta decay



β are stopped by aluminium shielding

Gamma decay



γ are stopped by a thick wall of concrete or lead

- Units:
  - Activity: 1 Bq = 1 decay / second
  - Dose: 1 Gy = 1 J/kg
  - Effective dose equivalent (biological dose): 1 Sv

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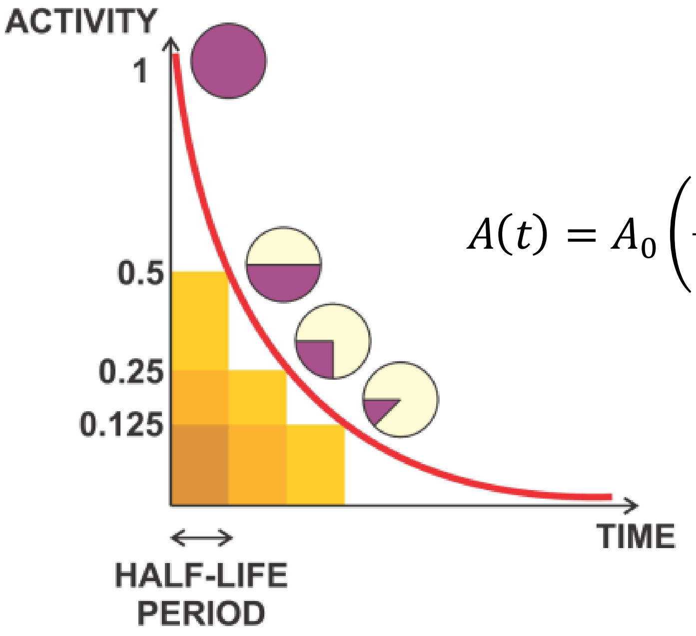
Radioactive waste: characteristics

- **Half-life period**: time required for the activity to reduce to half of its initial value

Isotope	Half-life ($t_{1/2}$)
^{222}Rn	4 days
^{131}I	8 days
^{134}Cs	2.06 years
^{90}Sr	28.9 years
^{14}C	5730 years
^{135}Cs	1.33 10^6 years
^{129}I	1.57 10^7 years
^{238}U	4.468 10^9 years



$$A(t) = A_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

Radioactive waste: various origins

Radioactive waste: classification

- **Low level waste (LLW)**

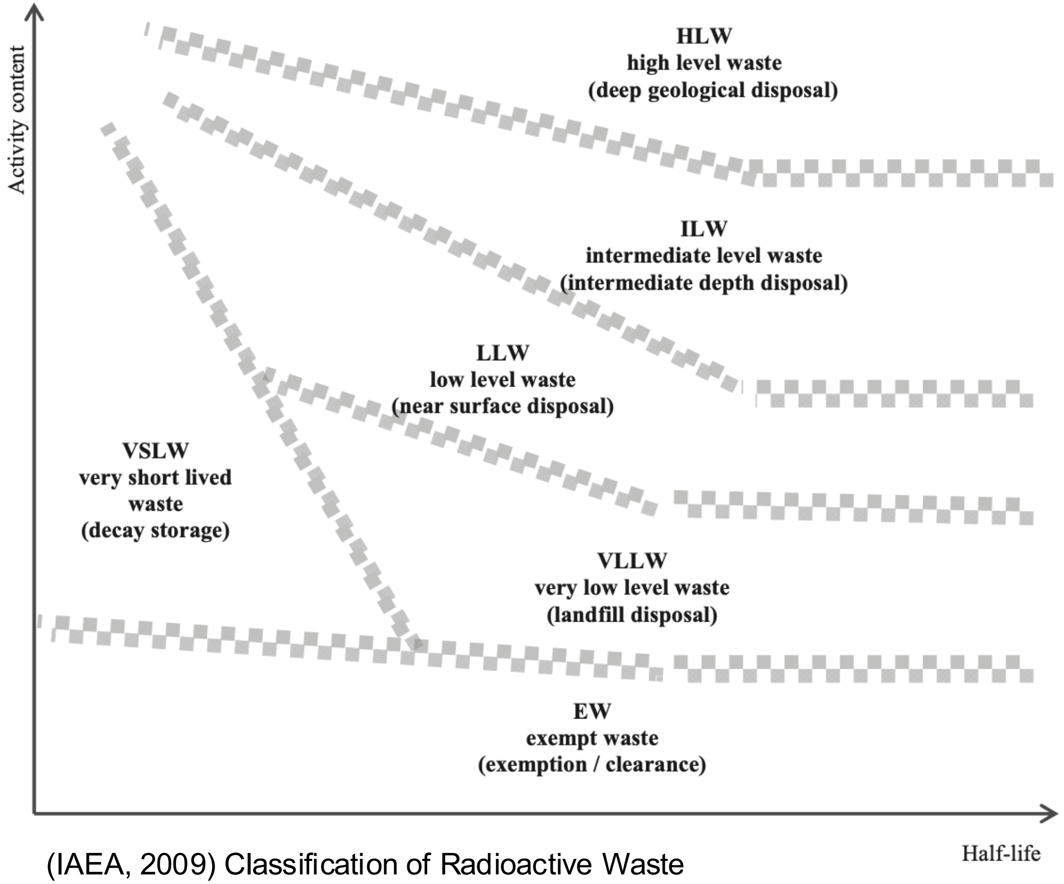
  Small amounts of radionuclides of short half-life. Not heat emitting.

- **Intermediate level waste (ILW)**

  Higher amounts of radioactivity, often they require shielding. Not heat emitting

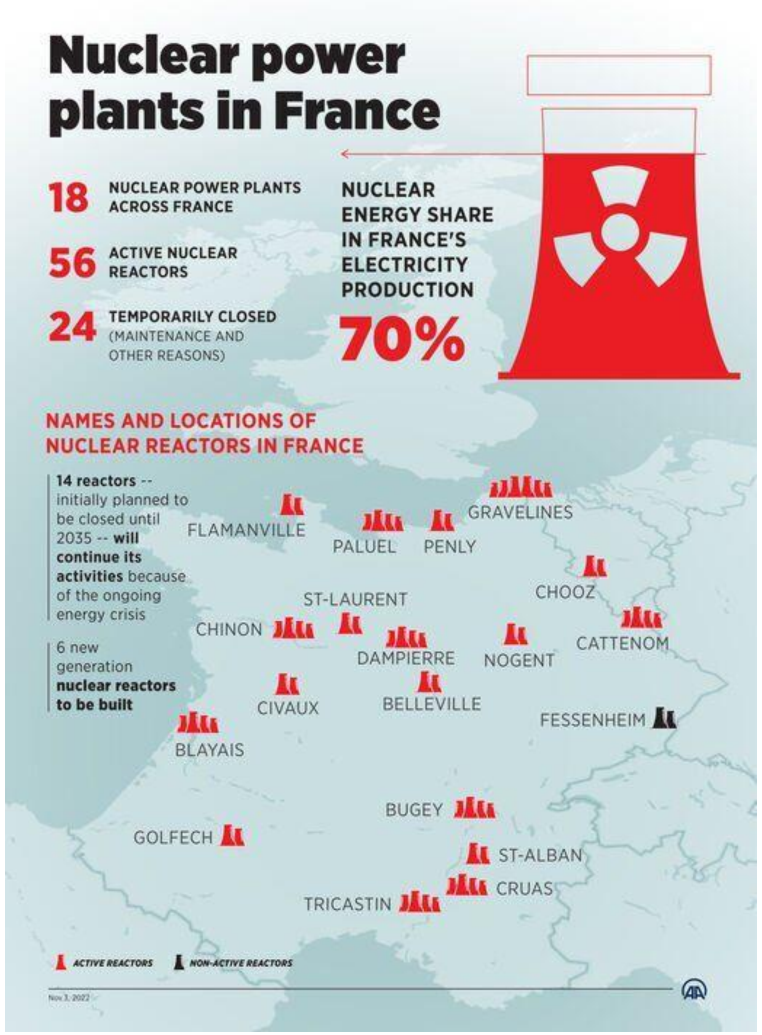
- **High level waste (HLW)**

  Large amounts of short- and long-lived radionuclides. Heat emitting. Two sources: spent fuel or solidified waste from reprocessing



(IAEA, 2009) Classification of Radioactive Waste

Radioactive waste: volume



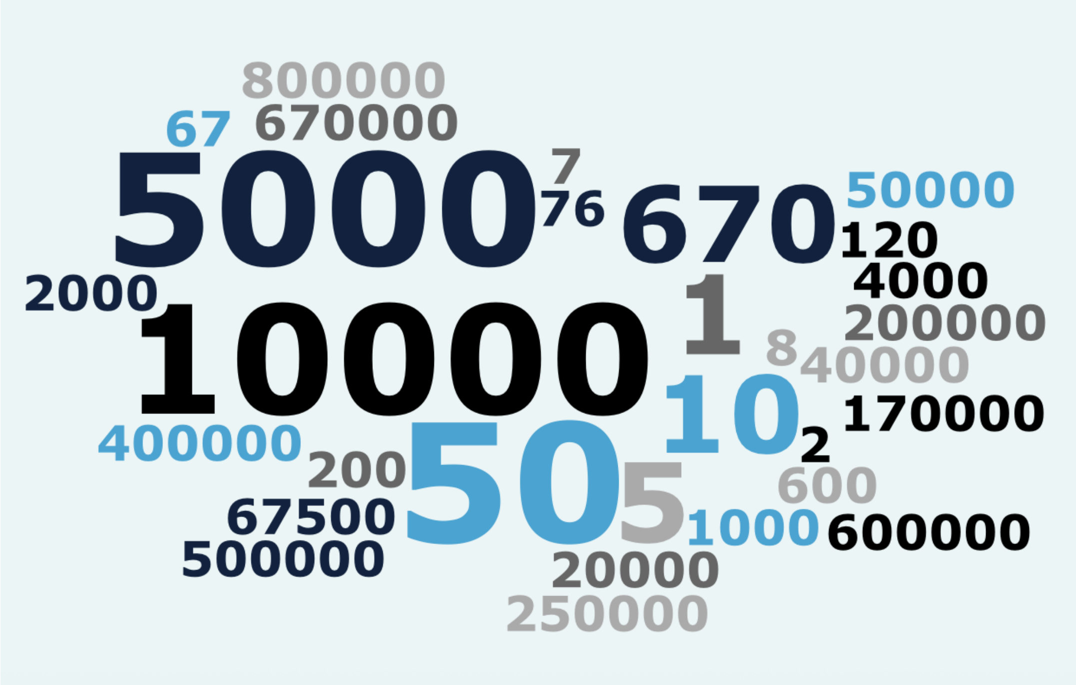
https://en.wikipedia.org/wiki/Container_ship

https://portshippingcontainers.com.au/containers-for-sale/general-purpose-containers/

~ 67 m^3

France has 56 active nuclear reactors. In 2023, what was the inventory in volume of high-level radioactive waste in France?

France has 56 active nuclear reactors. In 2023, what was the inventory in volume of high-level radioactive waste in France?



Mean: 95552.55

RESULTS SLIDE

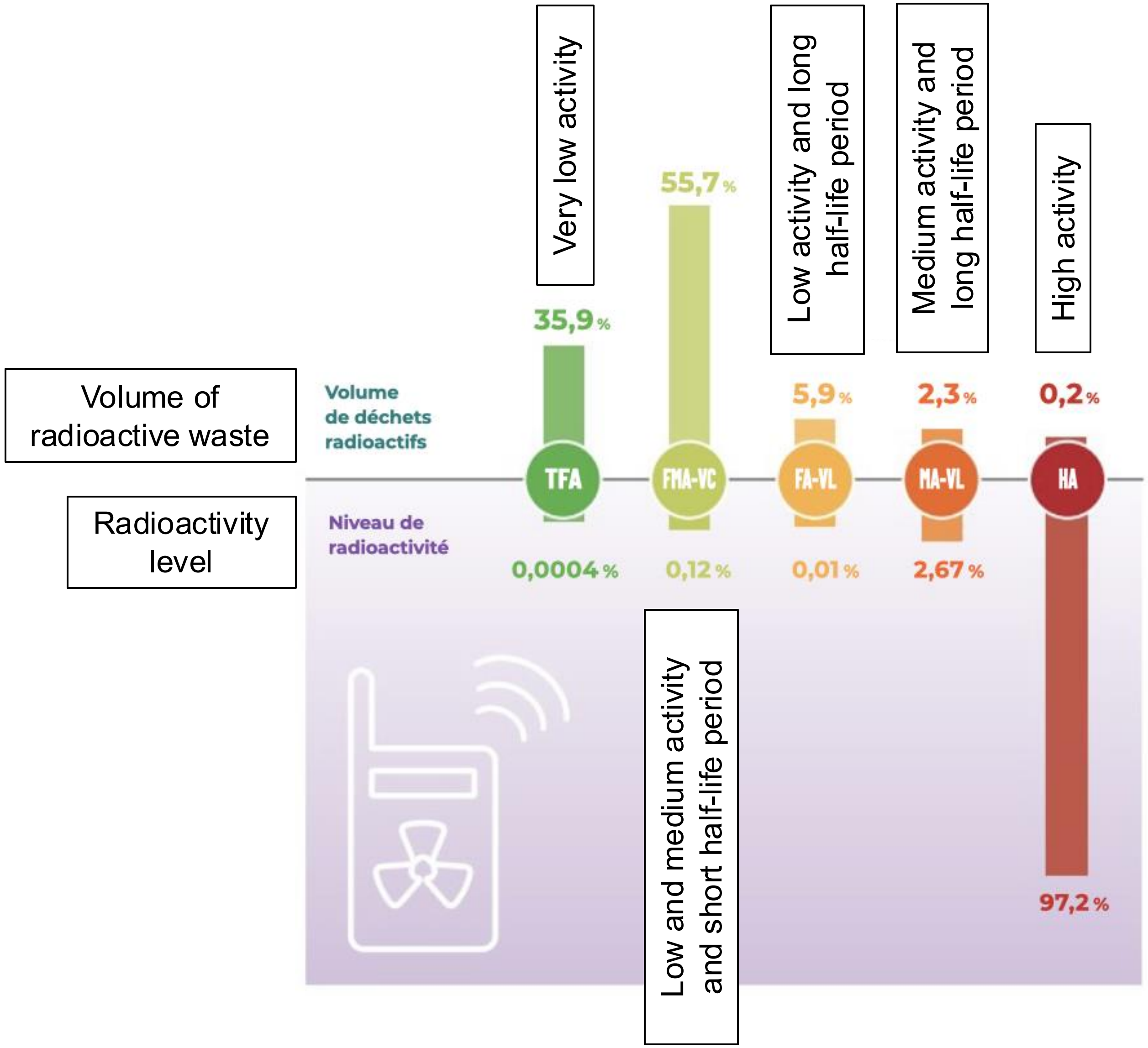
Radioactive waste: French inventory

INVENTORY AND DIFFERENCE IN VOLUMES (IN m^3) OF WASTE ALREADY DISPOSED OF OR DUE TO BE MANAGED BY ANDRA

Category	End of 2021 inventory	2021/2020 trend	# containers (end of 2021)
HLW	4320	+130	~ 64
ILW-LL	39500	-3400	~ 590
LLW-LL	103000	+9200	~ 1537
LILW-SL	981000	+10000	~ 14642
VLLW	633000	+47000	~ 9448
DSF	304	+9	~ 5
Total	~ 1,760,000	+60000	

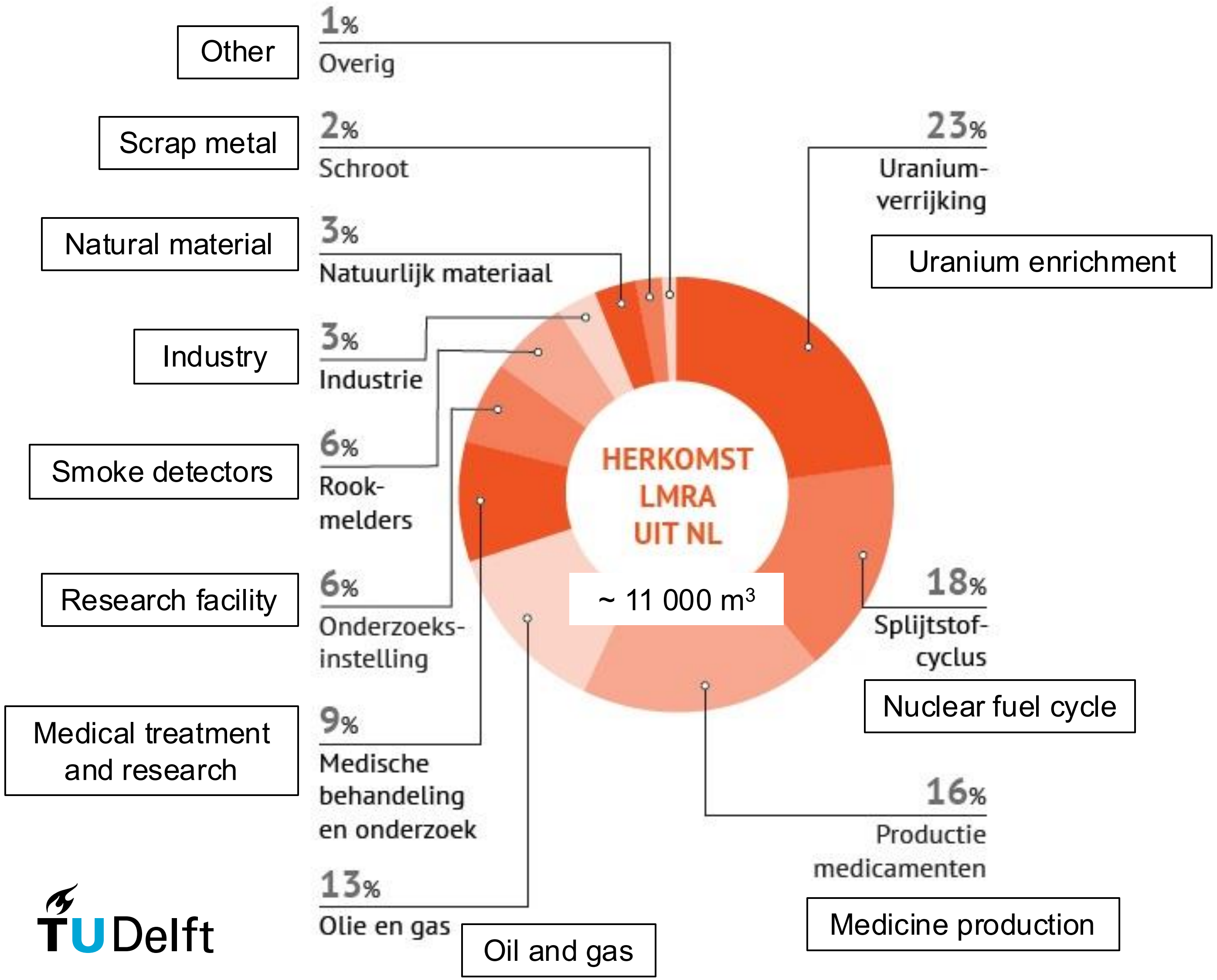
Andra (2023) https://inventaire.andra.fr/sites/default/files/pdf/20230316_-_andra_-_inventaire_national_-_essentiel_-en.pdf

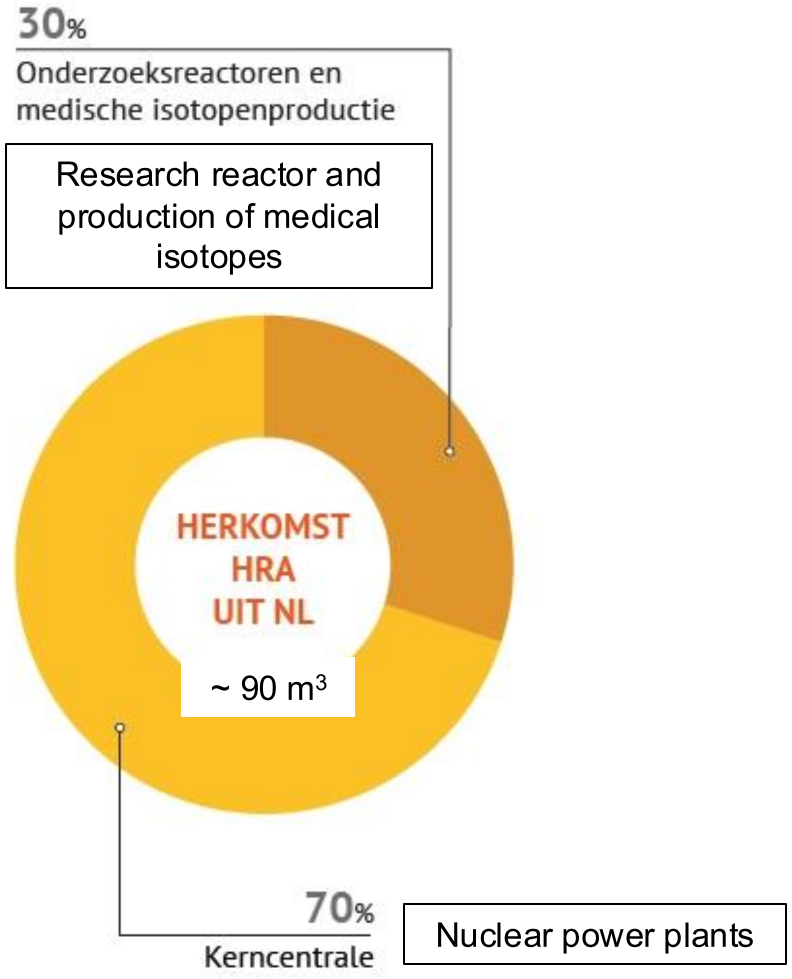
Radioactive waste: French inventory



ANDRA (2023)

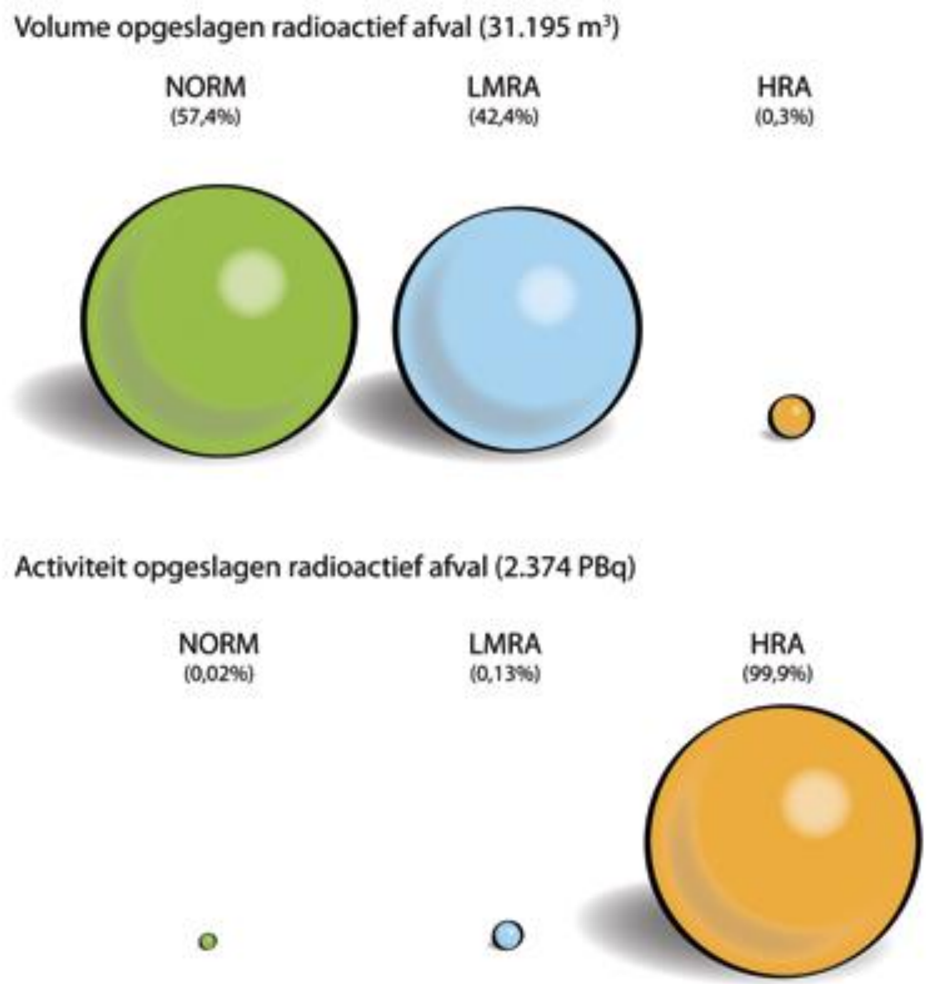
Radioactive waste: Dutch inventory





COVRA

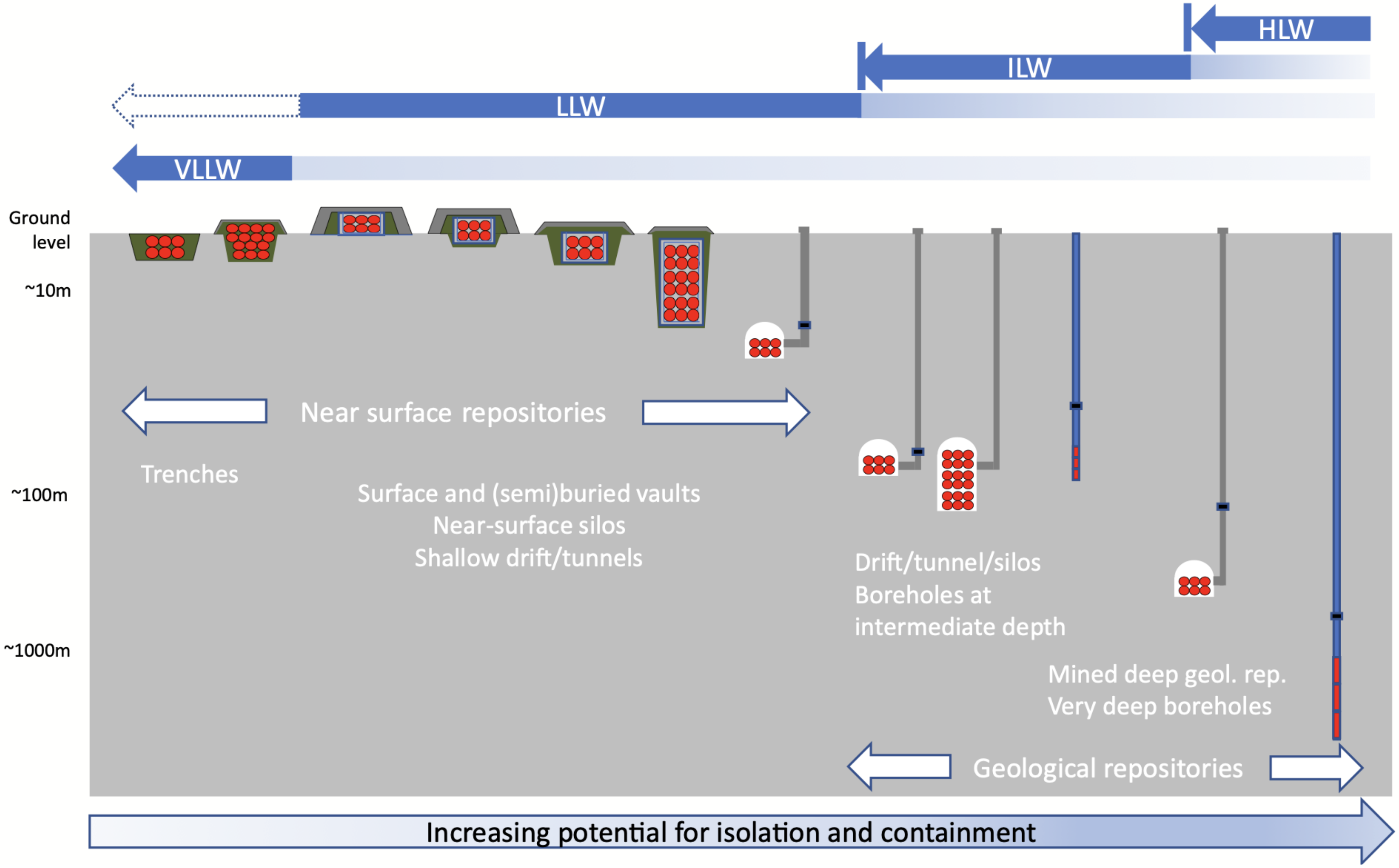
Radioactive waste: Dutch inventory



NORM = Naturally Occurring Radioactive Material
= wastes and residues from a wide range of industrial activities that are not part of the nuclear fuel cycle

COVRA (2016)

Radioactive waste: management solutions



IAEA (2020) Design Principles and Approaches for Radioactive Waste Repositories

Radioactive waste management programme

- The preferred waste management solution depends on the waste type and waste type volume
- Different countries have different strategies for the long-term isolation of their radioactive waste, especially of low-level radioactive waste
- Geological disposal programme typically follow 6 phases:
  1. Programme initiation
  2. Site identification and selection
  3. Site characterisation
  4. Construction
  5. Operation
  6. Closure

Safety first !

Increasing focus on optimising the resources needed to implement the safety strategy and safety concept

The rest of this lecture will focus on deep geological disposal facilities, which pose the greatest geomechanical challenges

Outline

1. General context of radioactive waste management
2. **General concepts of geological facilities for radioactive waste disposal**
3. Multiphysics processes
4. Geomechanical challenges:
    - Excavation Damaged Zone and clay host formation – support interaction
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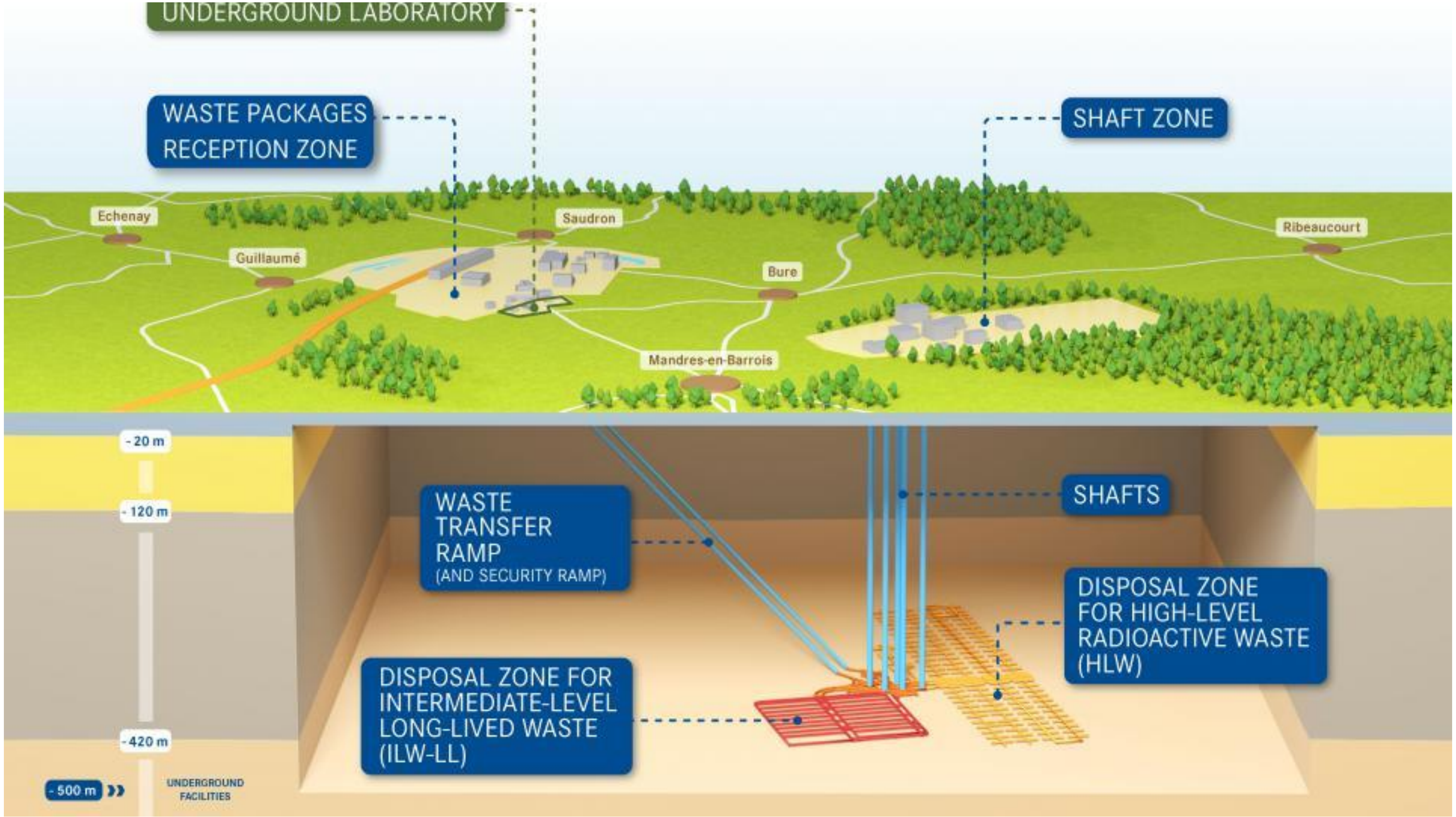
Geological disposal facility for radioactive waste



Andra

Geological disposal facility for radioactive waste

Objectives

1. **CONTAIN**

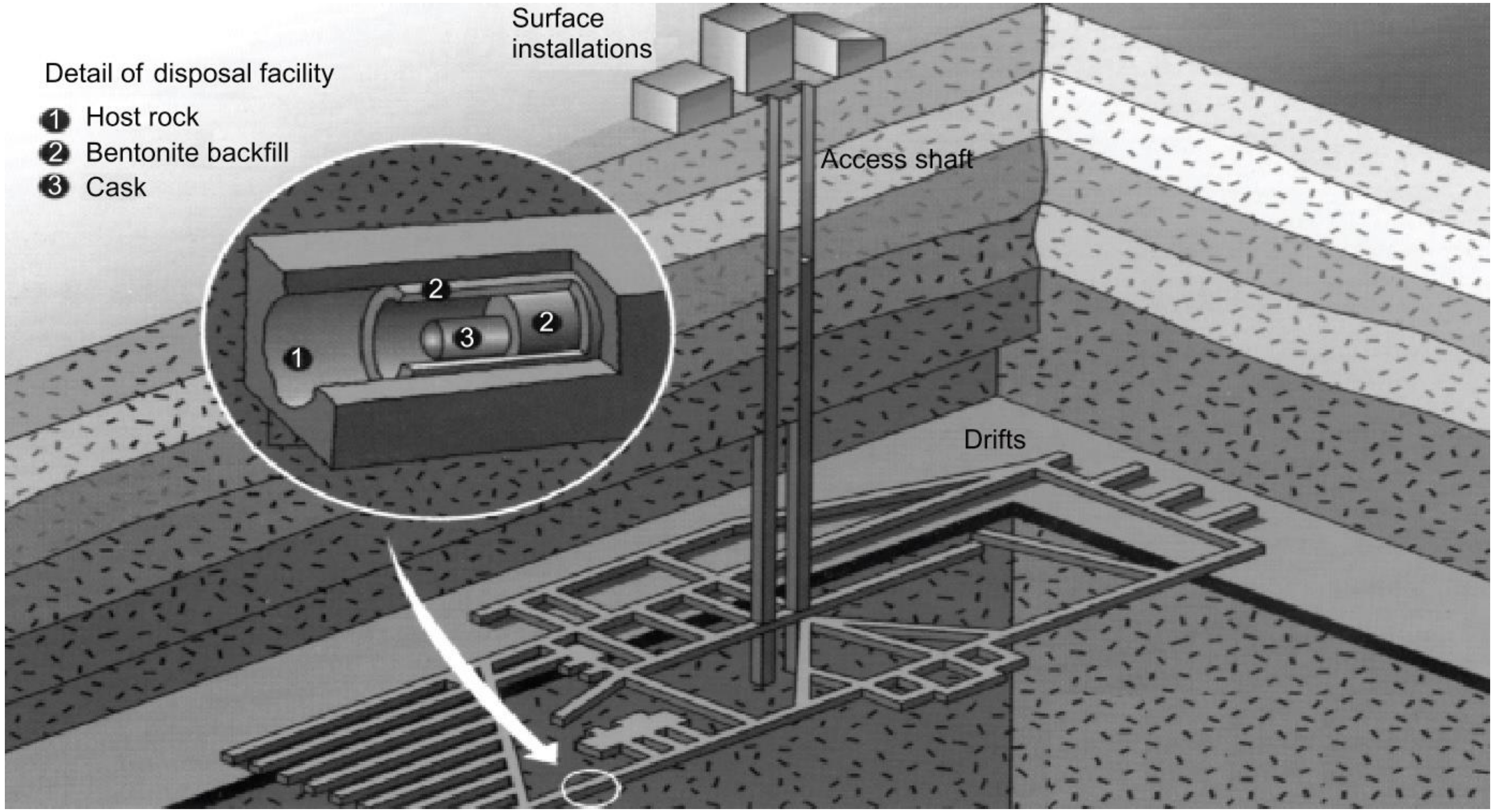
   Waste is removed from the human environment

2. **ISOLATE**

   Waste is isolated and contained for long periods of time

3. **RETARD**

   Only small release rates occur once complete isolation is over



Gens *et al.* (2009)

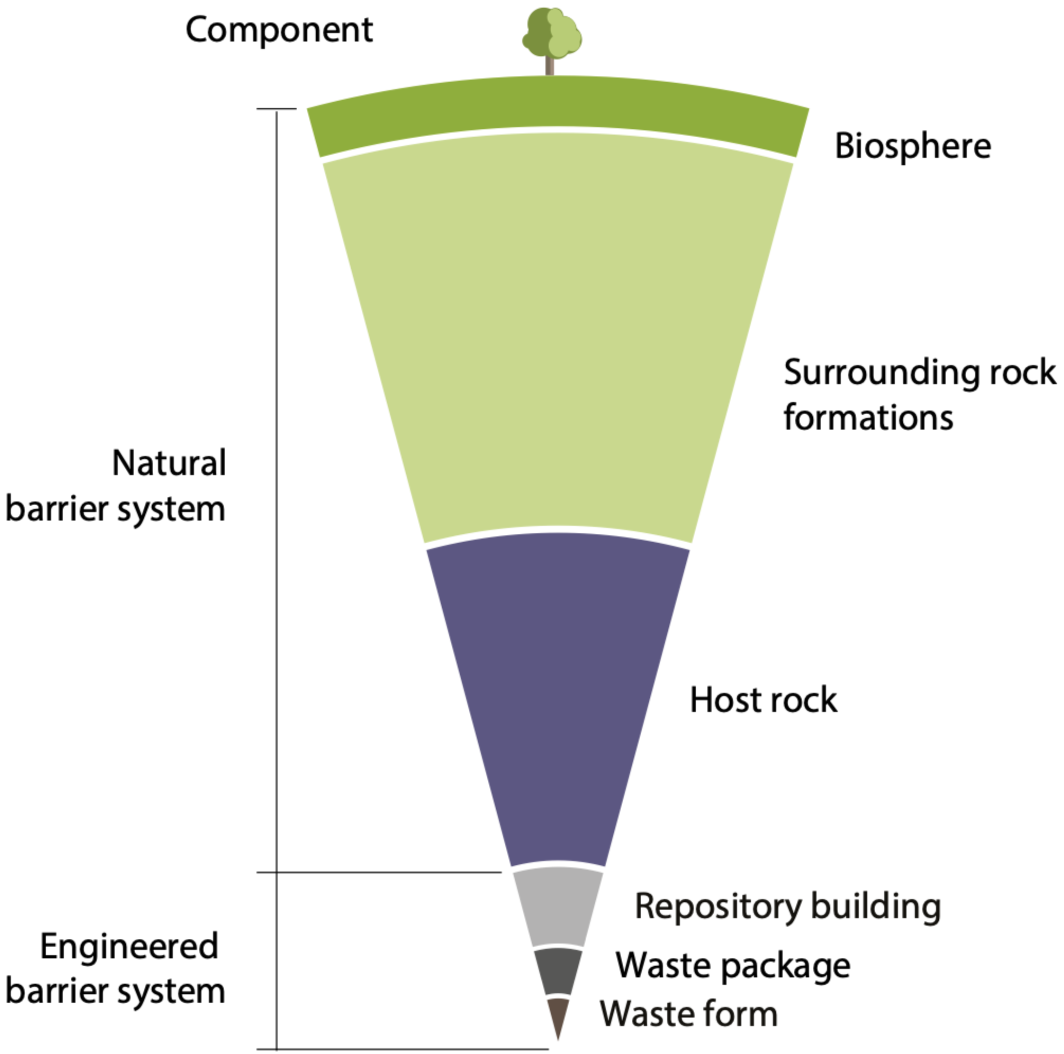
Multi-barrier system

- Safety is provided through a combination of
  - Natural barriers

    Host and overlying geological formations
  - Engineered barriers

    Waste form, waste package, and buffers, seals and backfills

- The natural and engineered barriers contain and isolate the radioactive waste and delay the migration of radionuclides



COVRA Safety Case (2024)

Natural barrier: crystalline rocks

- Low permeability
- High chemical stability
- Low economic value
- High strength

- Characterisation of fracture network may be difficult
- No self-healing capacity


Onkalo disposal facility for spent fuel (Finland) (Posiva Oy)


Josef URC (Czech Republic) //www.stolajosef.cz/)

Natural barrier: argillaceous rocks

- Large range of host formations, from plastic clays and indurated claystones
- Low permeability
- Significant radionuclides sorption capacity
- No economic value
- Strength not high, support is generally required
- More sensitive to chemical changes (oxidation)
- Significant self-healing properties (plastic clays)
- Uncertain capacity for self-healing (indurated claystones)

Mont Terri Rock Laboratory (Switzerland)
(TES)

HADES Underground Research Facility (Belgium)
(Euridice)

Natural barrier: salt rock

- Low permeability
- High creep rate, therefore material largely self-healing
- Some economic value, but not high
- Openings may require some support
- Vulnerable to freshwater entry
- Crushed salt used as material for engineered barriers

Geological salt beds deep underground in New Mexico (US Nuclear Regulatory Commission)

Morsleben repository (Germany) (BGE)

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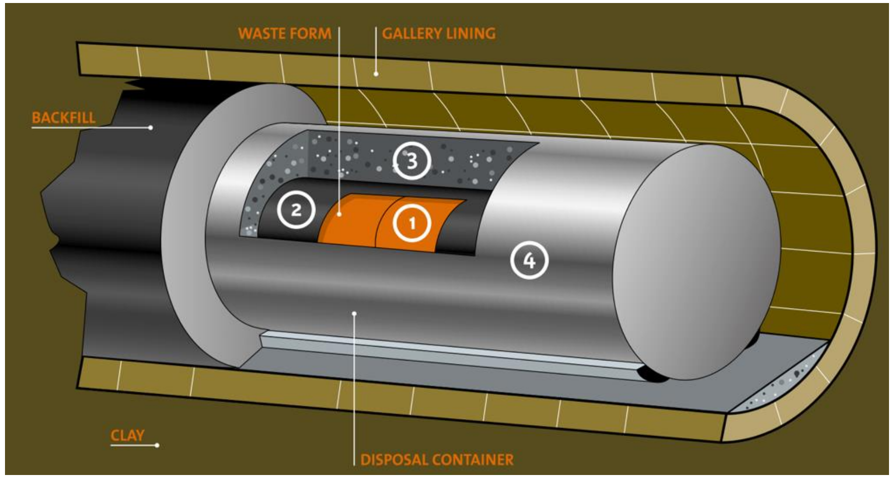
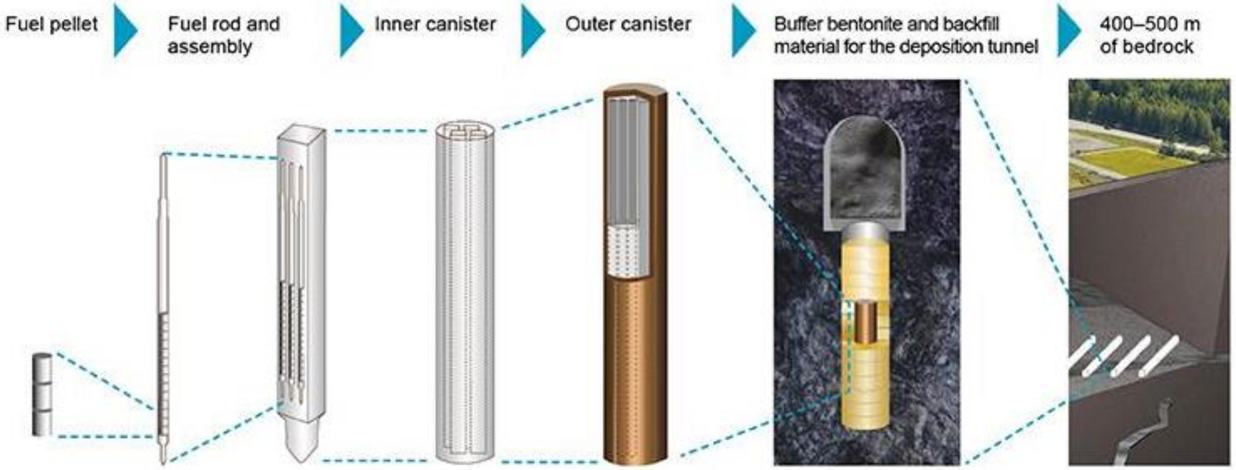
Engineered Barriers System (EBS)

- Waste form,
- Waste package
- Buffers, seals and backfills
- Depending on the concepts, the EBS either strongly relies on bentonites (Finland, France, Sweden, Switzerland) or on cement-based materials (Belgium, the Netherlands)



Belgian supercontainer concept (Euridice)



Finnish concept (Posiva)

Underground Research Laboratories (URLs)

Boom clay (plastic)
230m deep
Generic, purpose-built

COX argillite (hard clay)
450m – 520 m deep
Site-specific

Opalinus (hard) clay
400m deep
Generic, not purpose-built

(Euridice)

Granite
200m – 450 m deep
Generic, purpose-built

Rock salt
490m – 800m deep
Generic, not purpose-built

Granite
450m deep
Generic, not purpose-built

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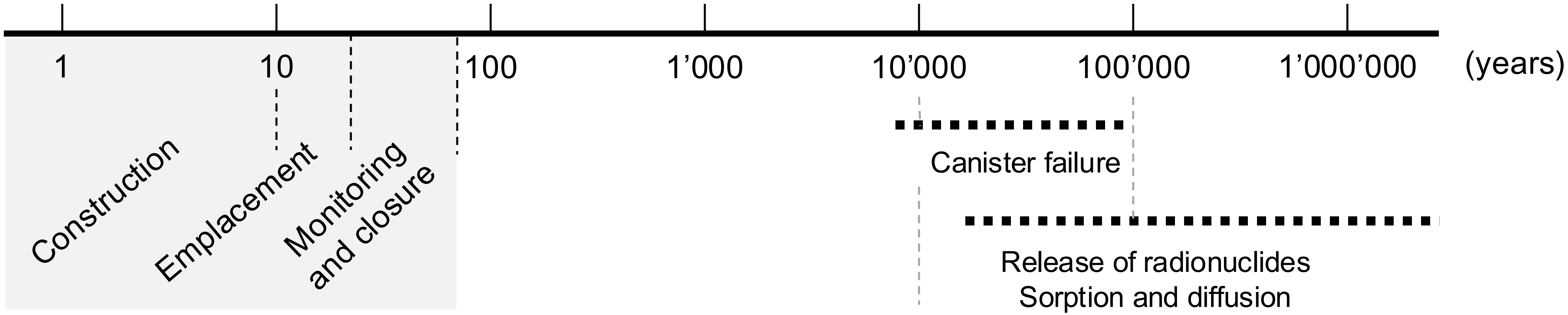
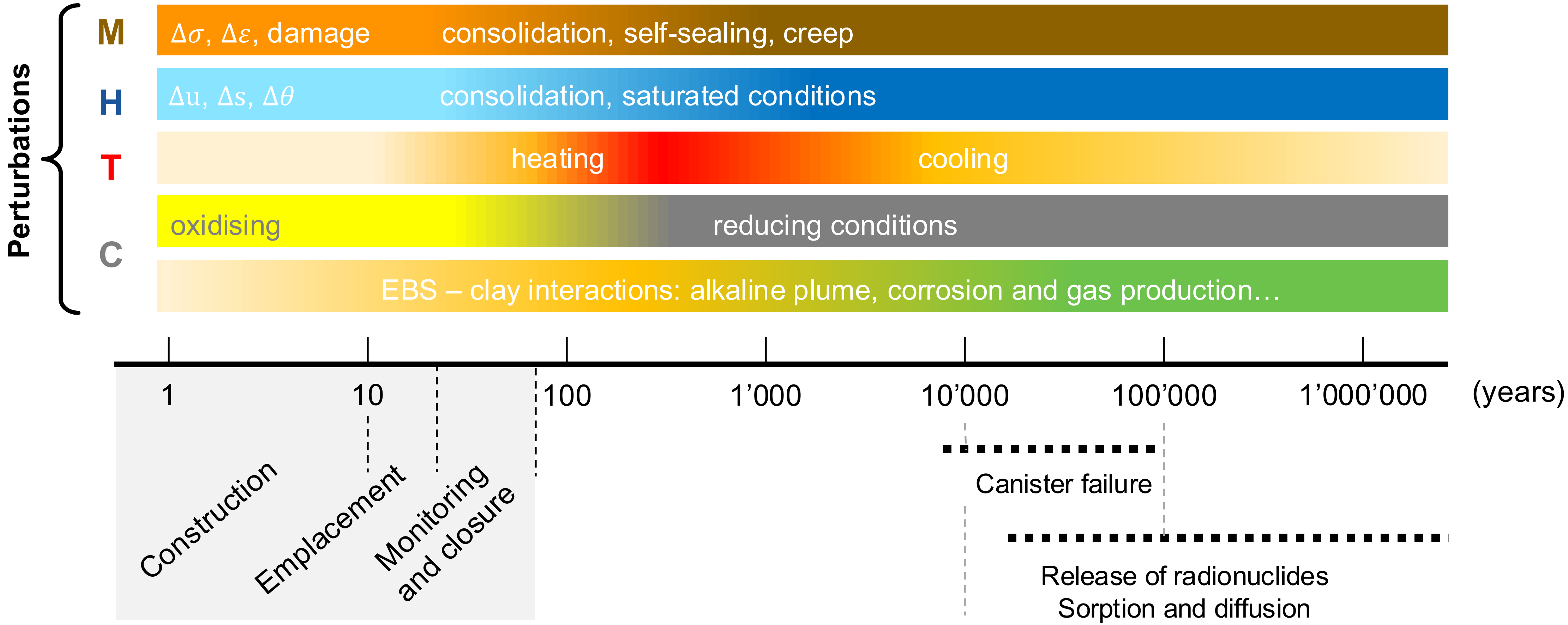
Multi-physics processes



Multi-physics processes



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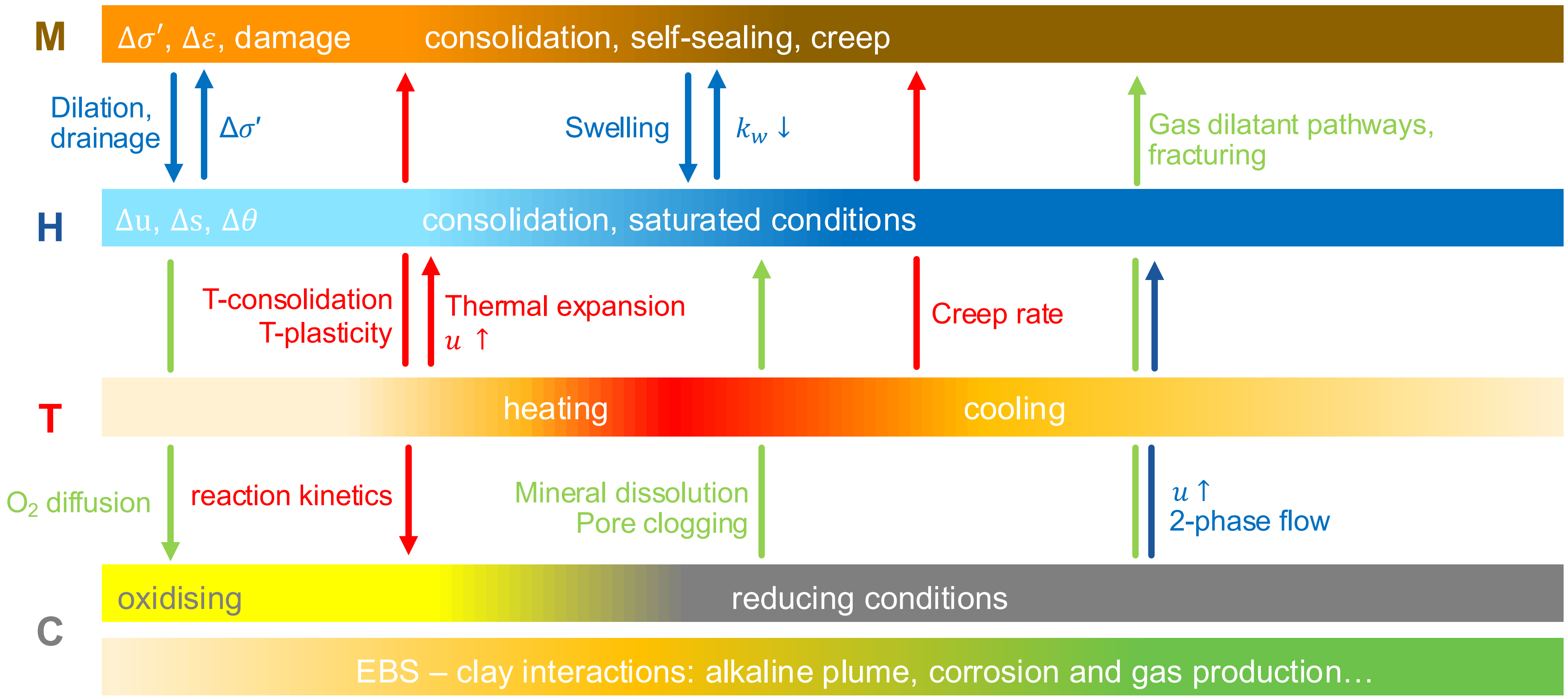
Multi-physics processes



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1. Excavation damaged zone (EDZ)

- Stress redistribution upon tunnel excavation
  - Due to the relatively low strength of clays, excavation leads to the creation of an EDZ
- Water drainage + ventilation

Kirsch equations (elastic)

Kirsch equations (elastic)

$$\sigma_r = \frac{\sigma_{x0} + \sigma_{y0}}{2}\left(1 - \frac{R^2}{r^2}\right) + \frac{\sigma_{x0} - \sigma_{y0}}{2}\left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right)\cos 2\theta$$

$$\sigma_\theta = \frac{\sigma_{x0} + \sigma_{y0}}{2}\left(1 + \frac{R^2}{r^2}\right) - \frac{\sigma_{x0} - \sigma_{y0}}{2}\left(1 + \frac{3R^4}{r^4}\right)\cos 2\theta$$

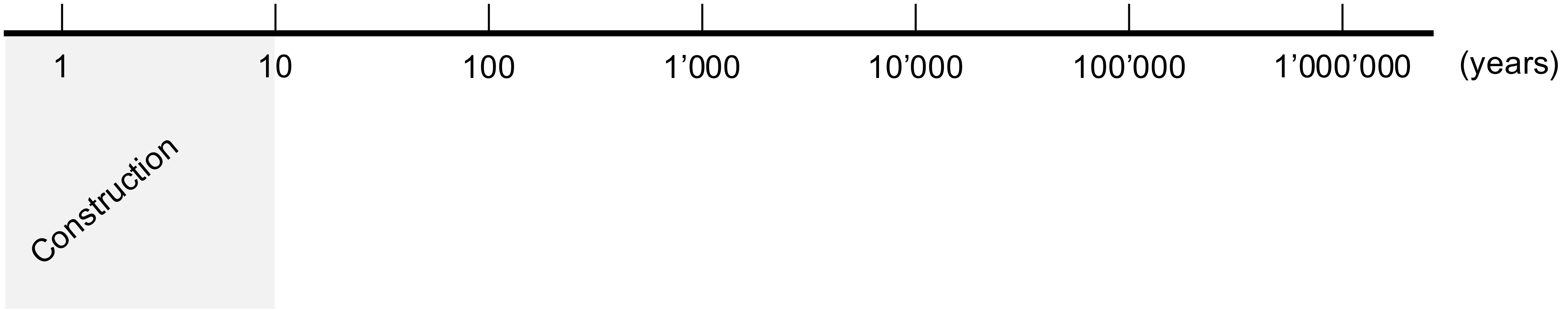
$$\tau_{r\theta} = -\frac{\sigma_{x0} - \sigma_{y0}}{2}\left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right)\sin 2\theta$$

For $r = R$:

$$\sigma_r = 0$$

$$\sigma_\theta = (\sigma_{x0} + \sigma_{y0}) - 2(\sigma_{x0} - \sigma_{y0})\cos 2\theta$$

$$\tau_{r\theta} = 0$$



1. Excavation damaged zone (EDZ)

Pre-excavation state of stress

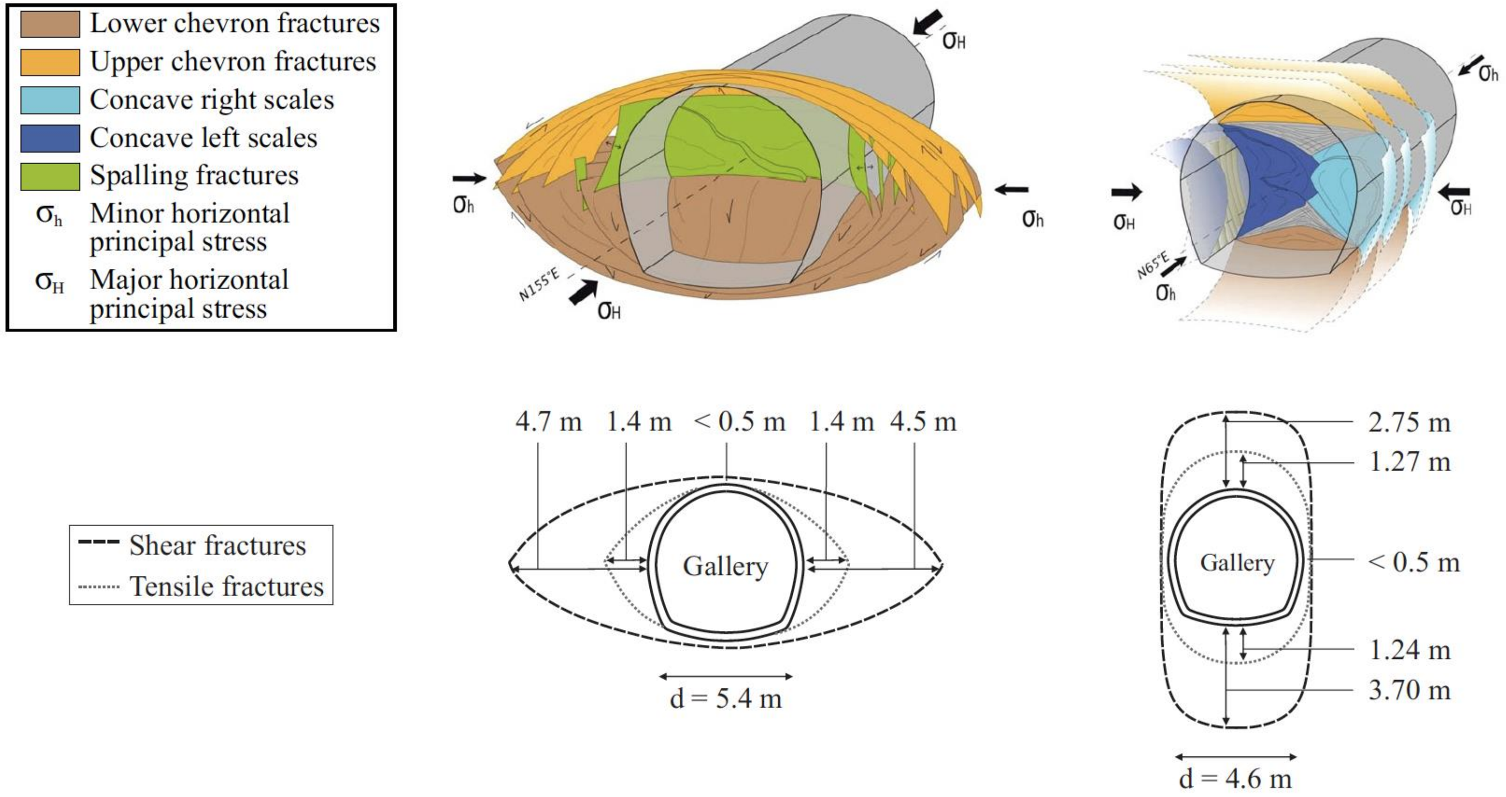
(Meuse/Haute-Marne URL)

$\sigma_v = 12 - 12.7$ MPa

$\sigma_h = 12 - 12.4$ MPa

$\sigma_H = 14.4 - 16.1$ MPa

$p_w = 4.5 - 4.7$ MPa



Pardoen (2015), after Armand *et al.* (2014) Geometry and Properties of the Excavation-Induced Fractures at the Meuse/Haute-Marne URL Drifts

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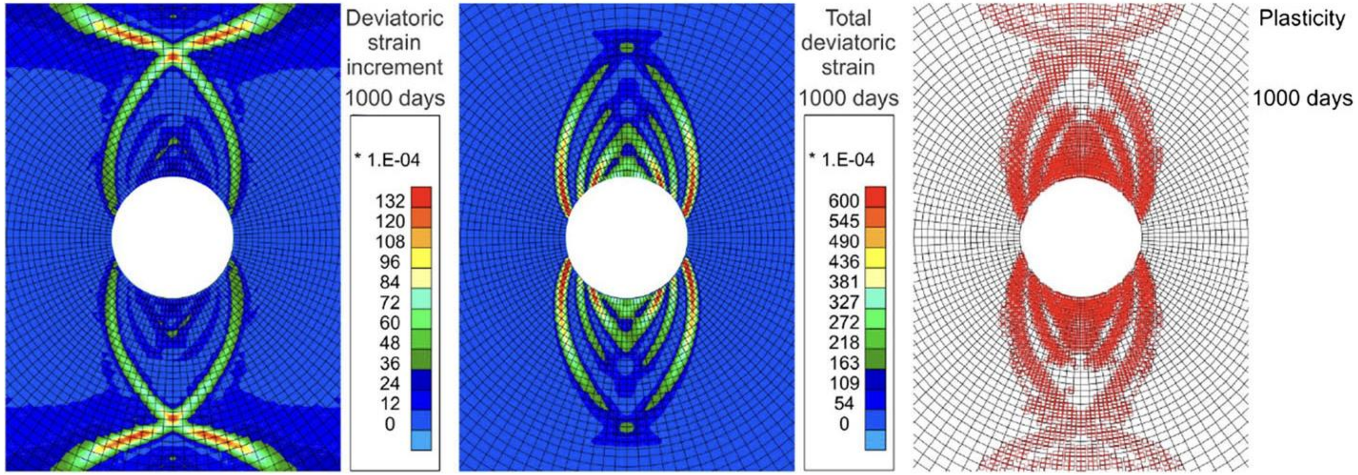
1. Excavation damaged zone (EDZ)

- Anisotropy of the initial state of stress
- Anisotropy of the material behaviour
- Localised damage
- Water drainage + ventilation
- Increase in hydraulic conductivity within the EDZ

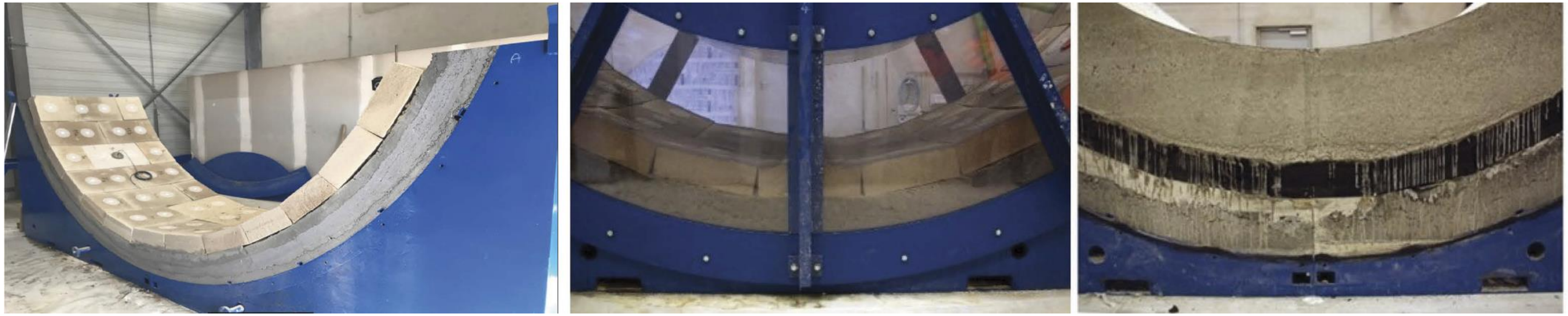
Complex, strongly coupled hydro-mechanical behaviour



Pardoen *et al.* (2015) Using Local Second Gradient Model and Shear Strain Localisation to Model the Excavation Damaged Zone in Unsaturated Claystone

1. Clay host formation – support interaction

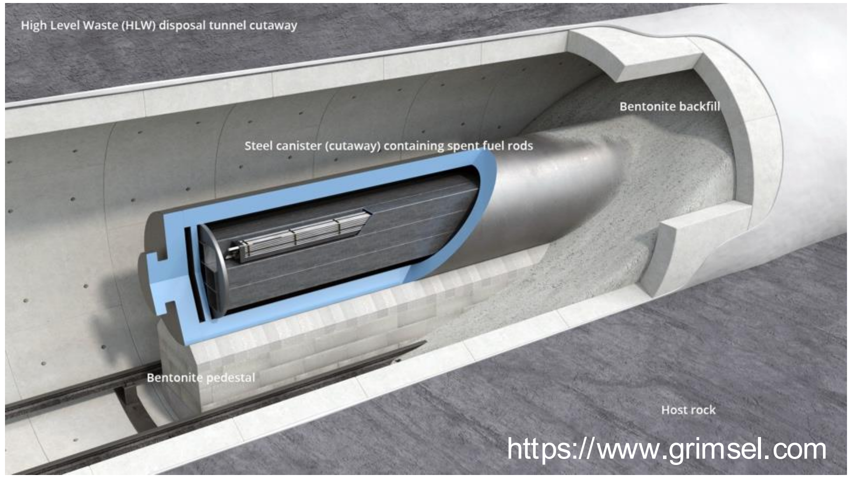
- Necessary tunnel support in (weak) clay formations to maintain the tunnel open during operation (and post-closure period)
- Represent a major cost item of a disposal facility
- What are the criteria for the design of a support?
- How to optimise the design of a support?

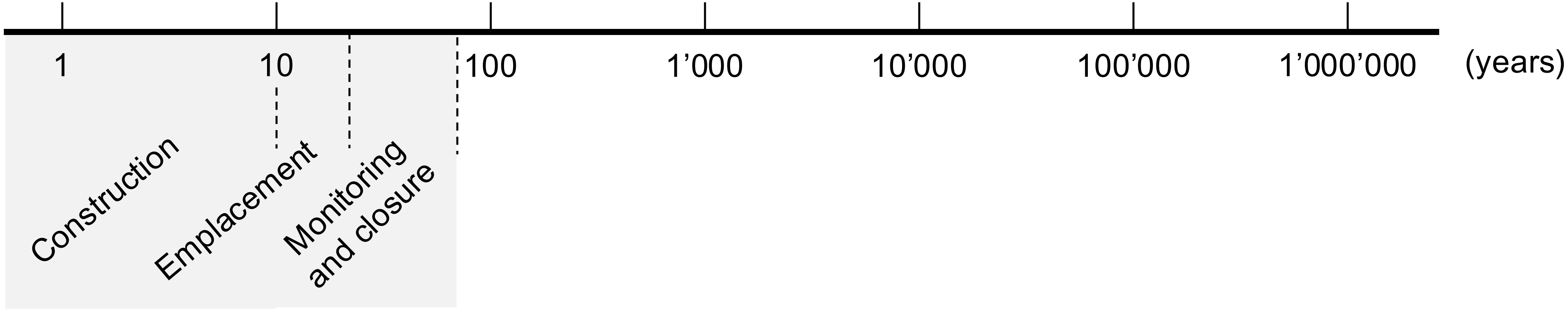


Zghondi *et al.* (2023) Compressible linings solutions: A multi-scale mechanical and technical demonstration up to a full 6m diameter surface loading "accelerator" device

2. Buffer, seal and backfill behaviour

- Tens to hundreds of km of disposal tunnels and access to be backfilled and sealed
- Most concepts rely on bentonite-based materials (compacted blocks, granular), crushed host rock, or a mixture of these





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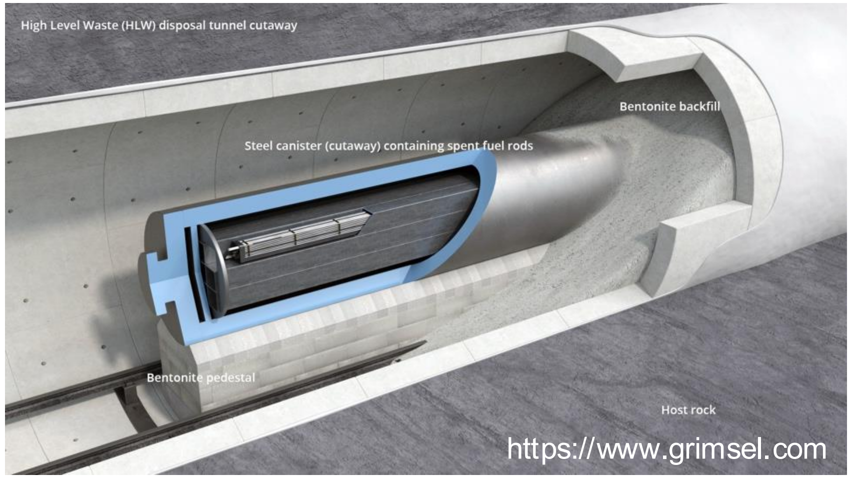
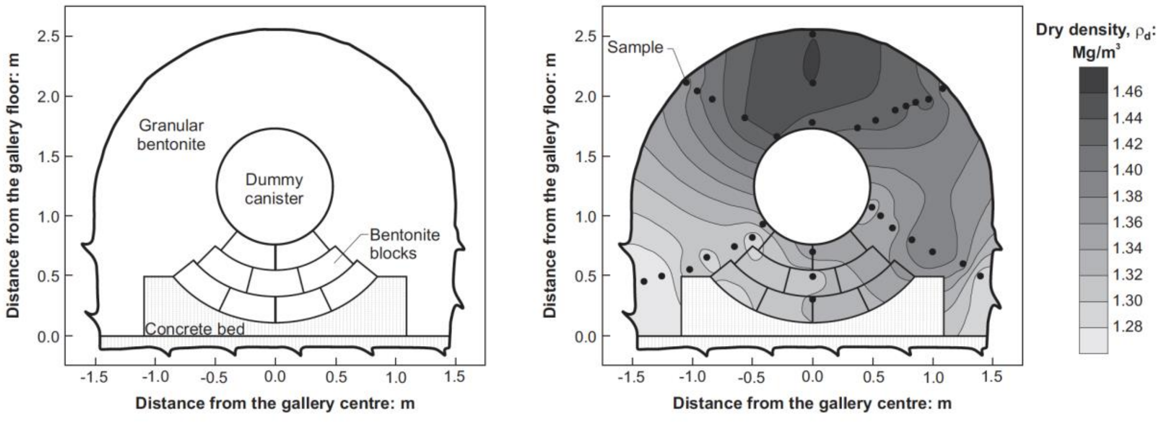




(a) Experimental set-up. (b) Dry density profile after dismantling.

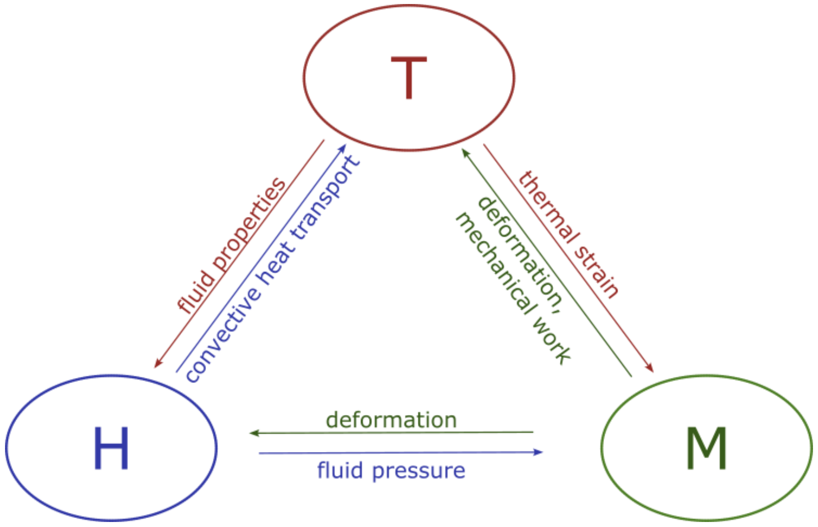
Mayor & Velasco (2014) EB dismantling

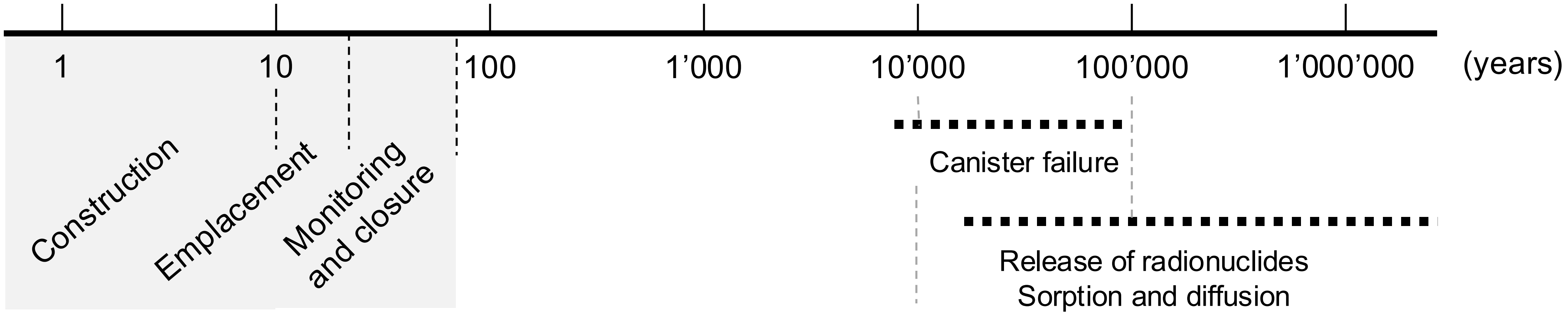
- Behaviour is affected by
  - THMC loads
  - Dry density
  - Pore water fluid
  - Boundary conditions
  - Scale ?
  - Time
  - Composition
  - …

→ Need to develop reliable and robust numerical models able to model the time-dependent response

3. Temperature effects

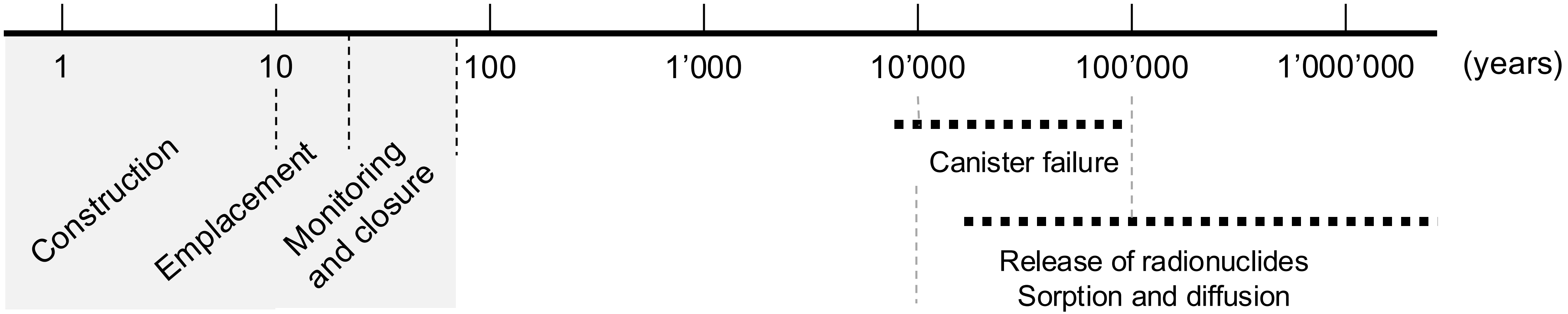
- Most safety cases target a maximum temperature of 90°C in the clay host formation
- This generally limits the distance between consecutive disposal tunnels
- Can we further optimise geological disposal facilities by allowing higher temperatures?





4. Gas transport

- Large amount of gas expected to be produced
    - Anaerobic corrosion of ferrous materials in metallic overpacks → H_2
    - Degradation of organic matter → CH_4 and CO_2
    - Radiolysis → H_2 (+ O_2, CO_2, CH_4,…)
    - α-decay → He



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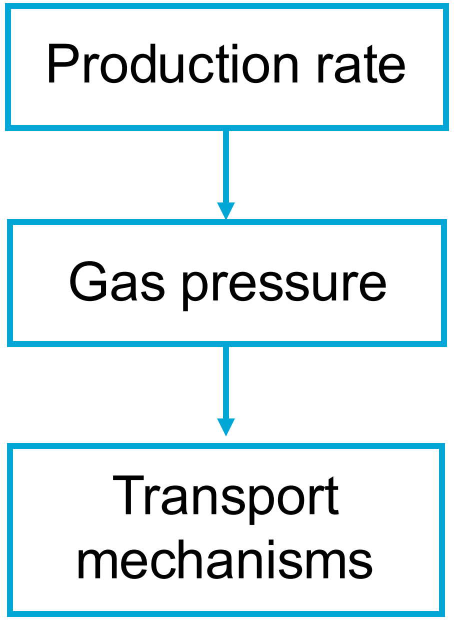


→ **How will this gas escape the repository?**

Can gas production and transport affect the barrier integrity and long-term repository performance ?

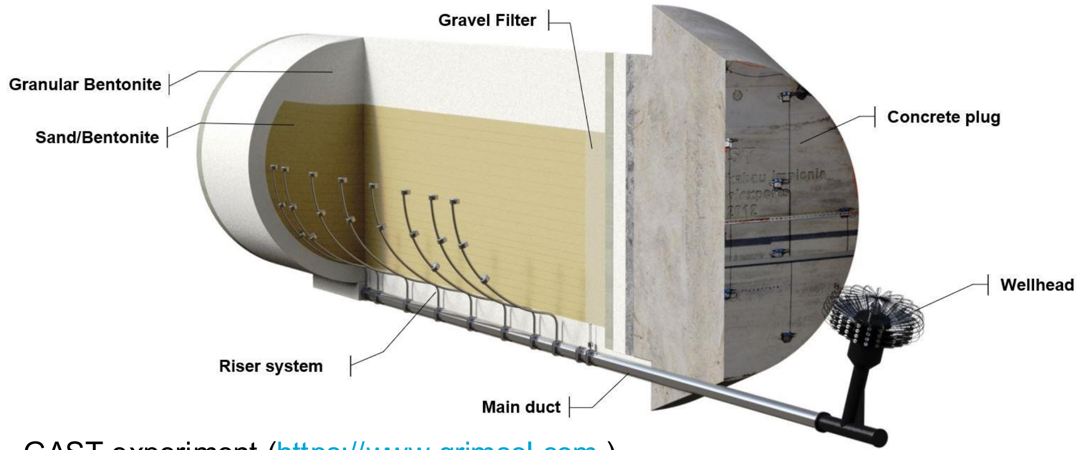
4. Gas transport

- Large amount of gas expected to be produced
  - Anaerobic corrosion of ferrous materials in metallic overpacks → H_2
  - Degradation of organic matter → CH_4 and CO_2
  - Radiolysis → H_2 (+ O_2, CO_2, CH_4,…)
  - α-decay → He

Production rate → Gas pressure → Transport mechanisms

→ **How will this gas escape the repository?**

Can gas production and transport affect the barrier integrity and long-term repository performance ?



GAST experiment (https://www.grimsel.com)

Outline

1. General context of radioactive waste management
2. General concepts of geological facilities for radioactive waste disposal
3. Multiphysics processes
4. Geomechanical challenges:
   - Excavation Damaged Zone and clay host formation – support interaction
   - Buffer, seal and backfill behaviour
   - Temperature effects
   - Gas transport
5. **Conclusions**

Conclusions

- Geological disposal facilities (GDFs) for radioactive waste are major civil engineering infrastructure (with tens of km of tunnels)
- Complex multi-physics processes will affect the GDF over very long timeframe
- There is a need for reliable, robust, modelling tools, accounting for uncertainties
- Given the long timeframe involved, there is a need for physics-based approach, based on a solid understanding of the materials and systems behaviour (hence the need for data)
- For early-stage programme, focus is on demonstrating the scientific concepts and technical feasibility. As programmes have developed, focus is increasingly on optimisation.
- Scope for contribution from our community is huge!

Geological disposal of radioactive waste

Technology & Evolution

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