sck cen
Belgian Nuclear Research Centre
Engineered and Geosystems Analysis / Expert Group Waste & Disposal
Institute for Sustainable Waste & Decommissioning

Vanessa Montoya - 21/07/2023

Radioactive waste management & repository research

Radioactive waste generation

Nuclear Energy:

The **generation of energy produces waste**. The **waste** produced in generating energy **must be managed** in ways that **safeguard human health** and **minimize the impact on the environment.**

For radioactive waste, this means **isolating or diluting** it such that **the rate / concentration of any radionuclides returned to the biosphere is harmless**. From nuclear power generation, unlike all other forms of energy generation, **all waste is regulated** – none is allowed to cause pollution.

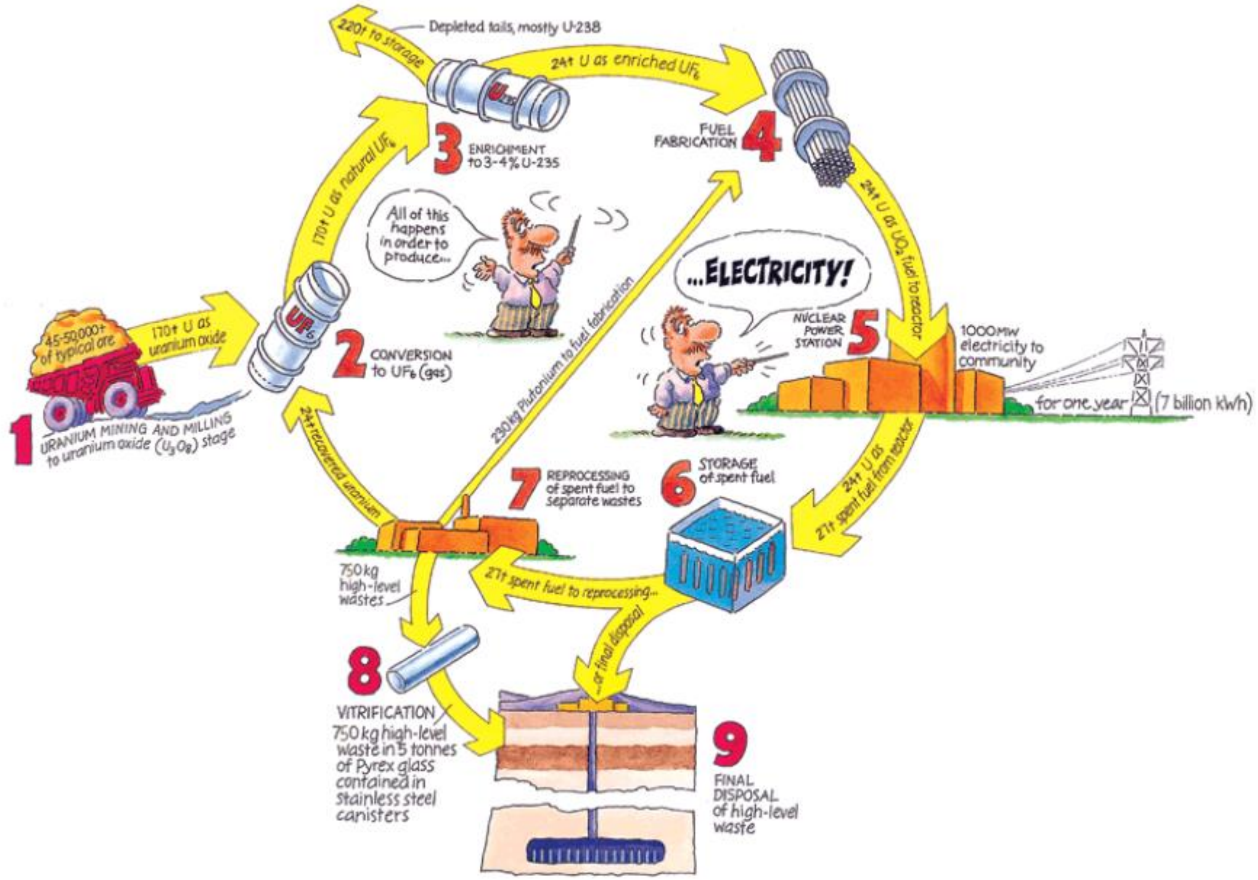
Radioactive waste generation

→ **Hospitals and research laboratories**

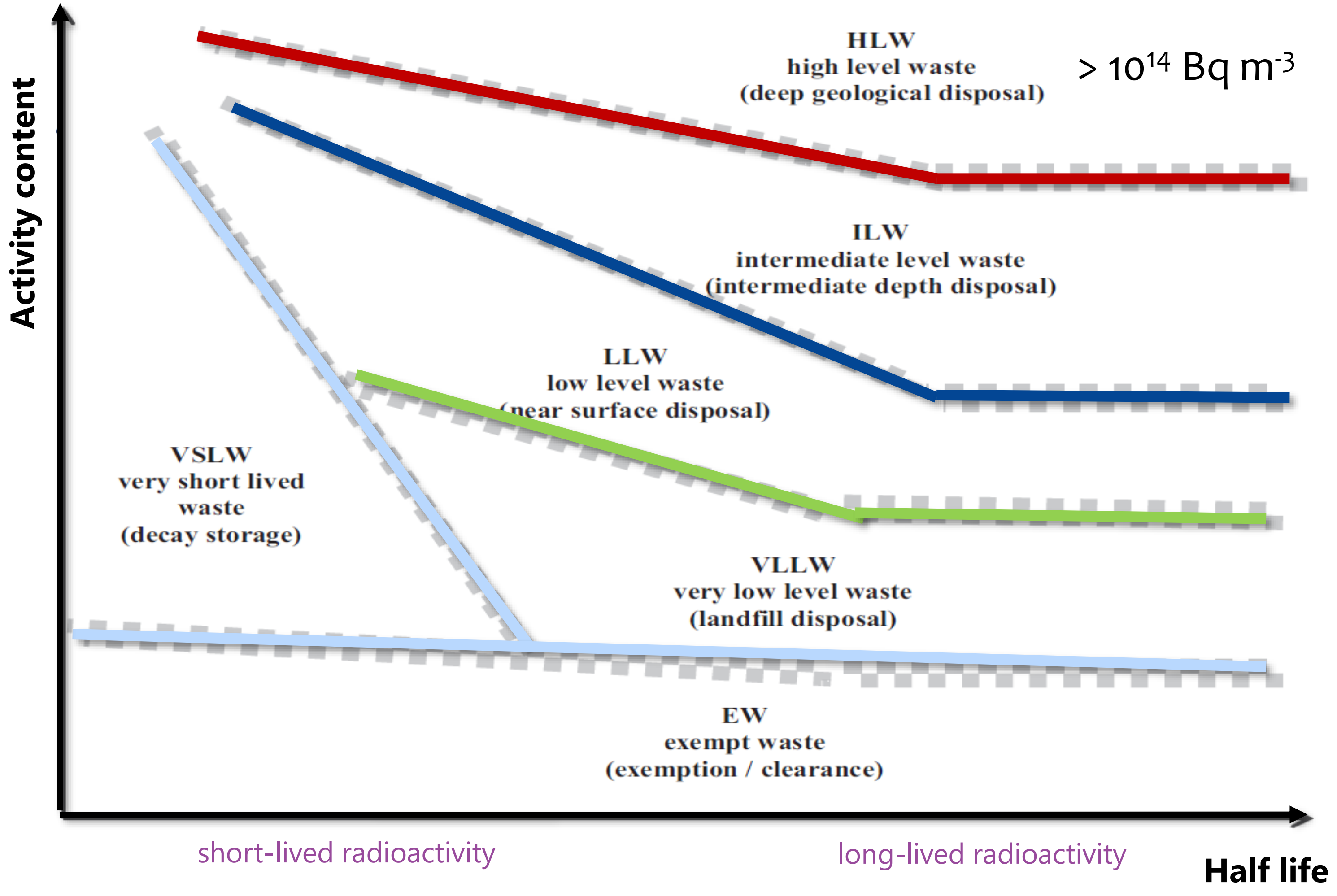
→ **Military programmes**

→ **Nuclear Energy Industry:**

- Mining and milling of uranium ores
- Fuel and Reprocessing
- Decommissioning



Classification of radioactive waste



HLW- High level waste (deep geological disposal

ILW - Intermediate level waste (intermediate depth disposal

LLW - Low level waste (near surface disposal)

VLLW – Very low level waste (landfill disposal)

**IAEA (2003) Radioactive Waste Management Glossary, ISBN 92-0-105303-7, Vienna

Classification of radioactive waste

Low level waste (LLW): is generated from hospitals, laboratories and industry, as well as the nuclear fuel cycle.

- It comprises **paper, rags, tools, clothing, filters**, …
- Contain small amounts of mostly **short-lived radioactivity**.

Classification of radioactive waste

Intermediate-level Waste (ILW) contains higher amounts of radioactivity and may require special shielding.

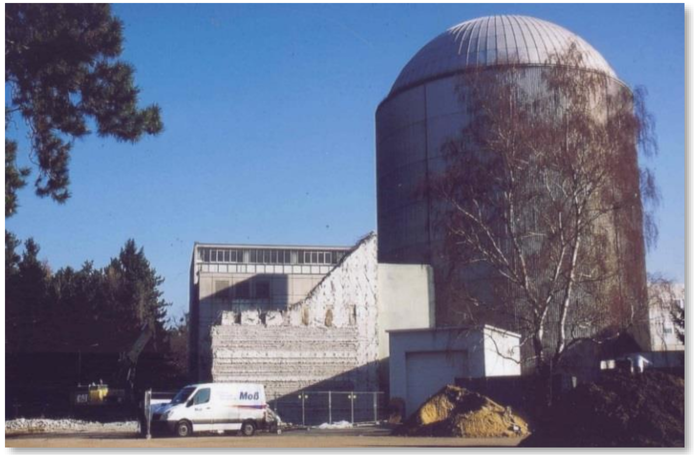
- It typically comprises **resins, chemical sludges, reactor components**, as well as contaminated materials from reactor decommissioning.
- Generally short-lived waste, mainly from reactors, but also long-lived waste from reprocessing nuclear fuel.
- It may be solidified in concrete or bitumen for disposal.

Worldwide it makes up 7% of the volume and has 4% of the radioactivity of all radwaste.

Classification of radioactive waste

Low and intermediate level waste

- Dominates waste stream (~95 vol% of total radwaste)
- Includes small portion of activity inventory
  (~1 % of total radioactive waste activity inventory)
- **Heterogeneous composition** of waste:
  Concrete, metals, resins, nitrates, plastics, rubber, chelates (EDTA ...), biomass (cellulose ...) etc.
- **Hardly characterized** / registered amount of radionuclides and waste matrix.
- Various waste products:
  Cemented waste drums, concrete shielded containers bitumized waste containers, compacted materials / metals, (...)

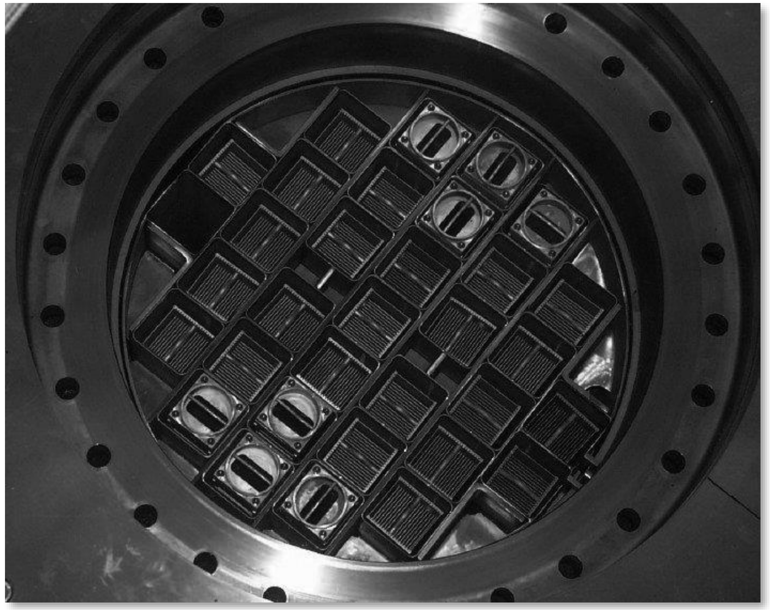


Contaminated lab waste; LLW / ILW drums at interim storage KTE Karlsruhe; reactor MZFR Karlsruhe, Germany

Classification of radioactive waste

High-level waste (HLW) arises from the 'burning' of uranium fuel in a nuclear reactor.

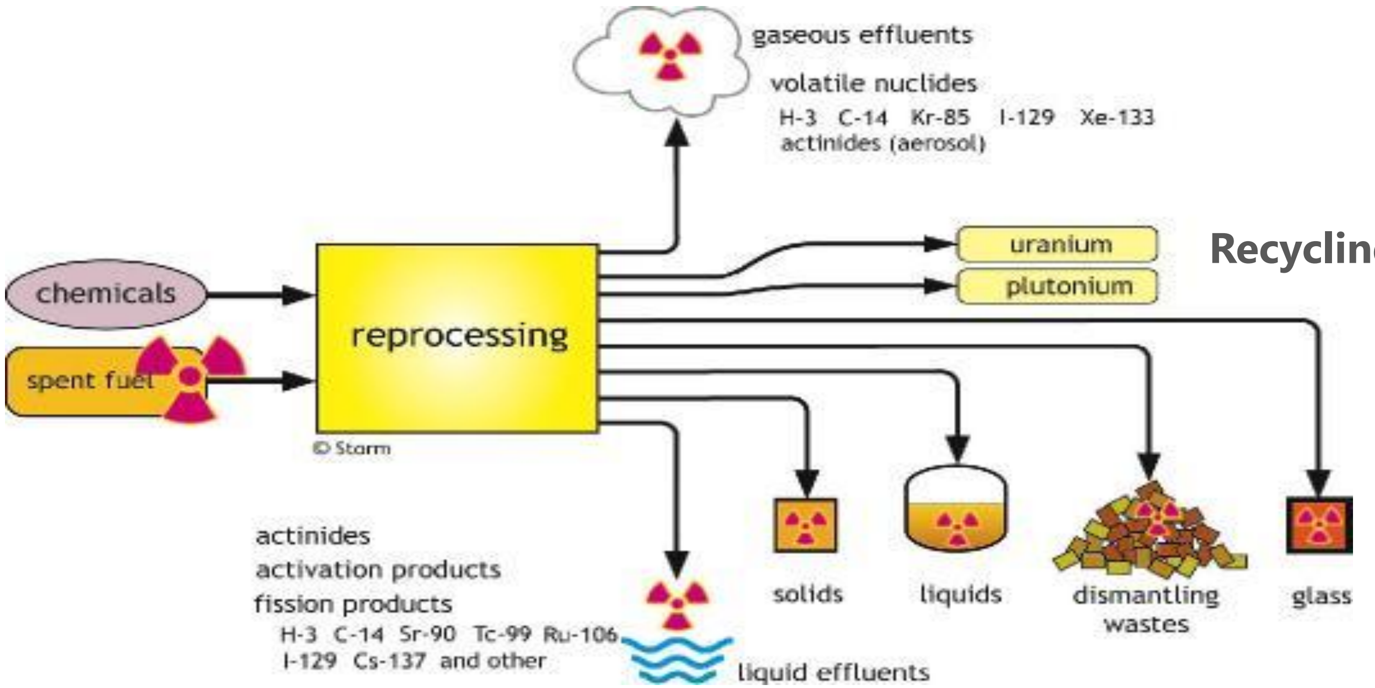
- It contains the **fission products** and transuranic elements generated in the reactor core.
- It is **highly radioactive** and hot due to decay heat, so requires cooling and shielding.
- It has **long-lived and short-lived** components.



Classification of radioactive waste

High-level waste (HLW)

- Spent fuel itself.
- Separated waste from reprocessing the used fuel



Recycling spent fuel

Classification of radioactive waste

Distribution of radioactive waste

Low - medium level waste < 10^{15} Bq / m^3

Operational waste of:
- Nuclear power plants, reprocessing plants, fuel production (...)

Construction materials of dismantled plants
Nuclear medicine facilities
Research facilities
Industrial applications, (...)

High level waste (mainly spent nuclear fuel)

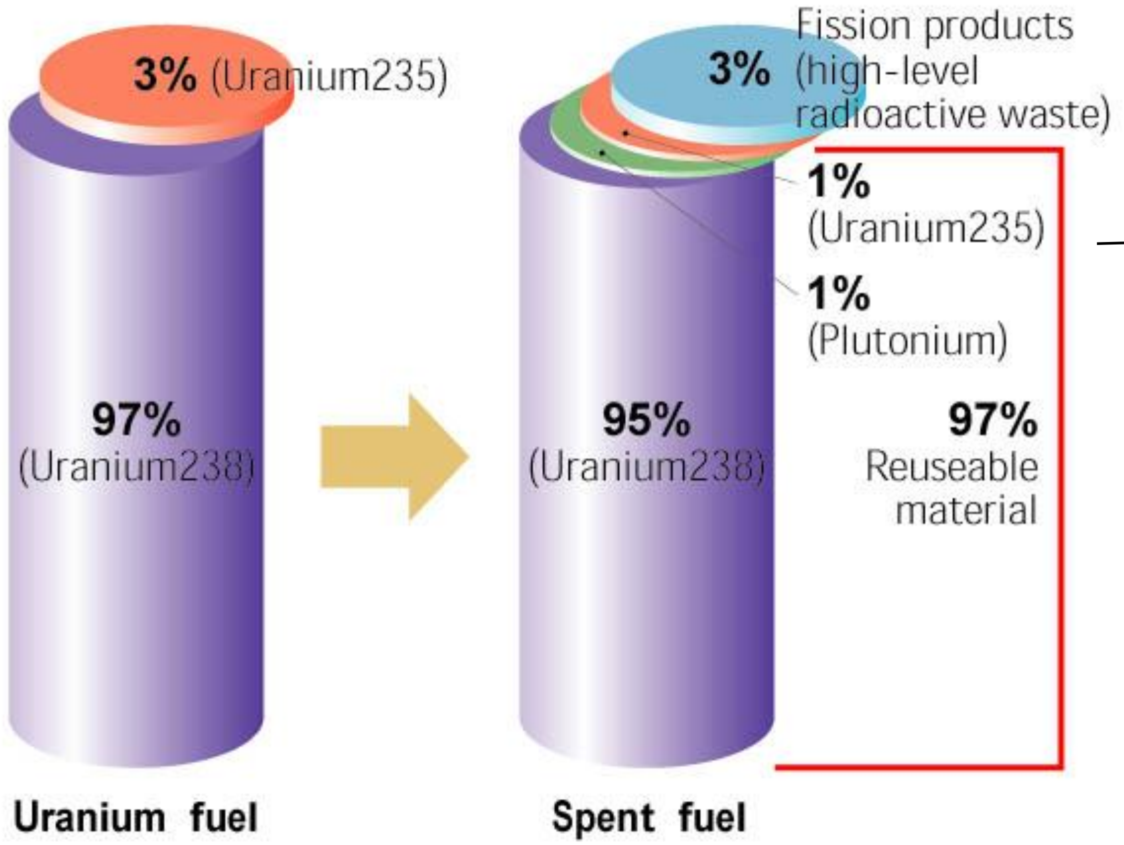
Spent nuclear fuel: radionuclides in UOx matrix
Vitrified waste: radionuclides in glass matrix from reprocessing

~95% of total waste volume
~ 1% of radioactivity

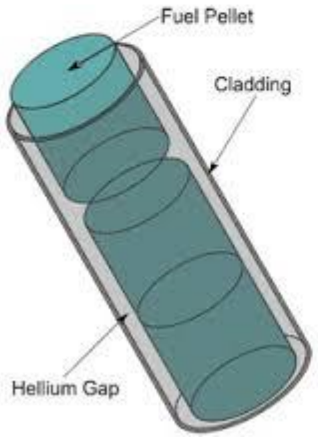
~ 5% of total waste volume
~99% of radioactivity

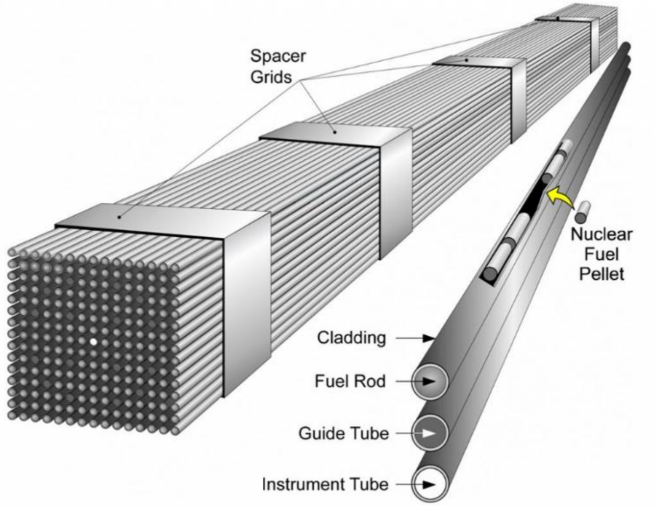
Radioactive waste – Spent fuel

Composition of spent nuclear fuel – HLW



UO_x pellets





Radioactive waste – Spent fuel

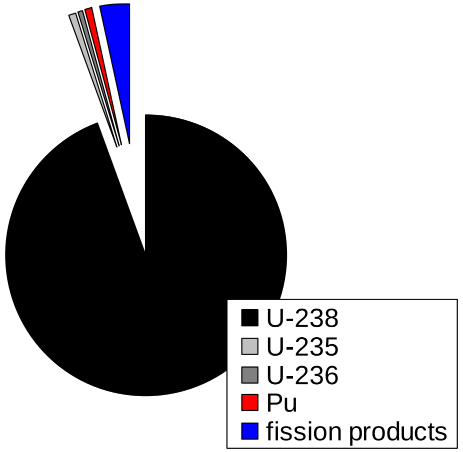
Composition of spent nuclear fuel – HLW

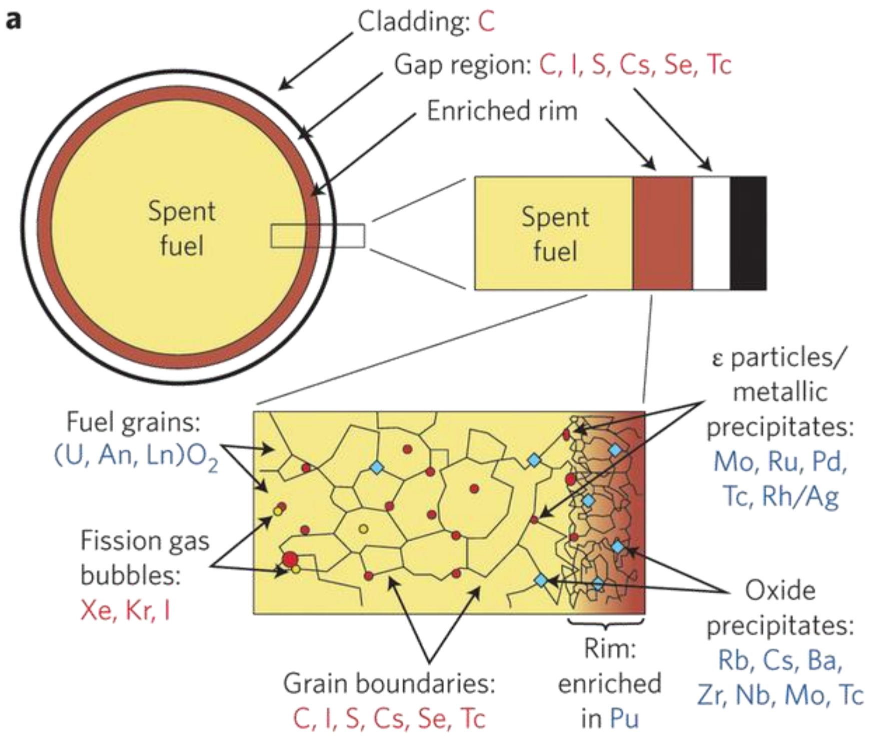
40 GWd/t burn-up after 3 -5 years cooling time in LWR
(Gigawatts-day /tonnes)

~**95 wt% UO_2** matrix: 94.3 wt% ^{238}U, 0.98 wt% ^{235}U

- 0.4 wt% ^{236}U (produced via neutron capture ^{235}U)
- ~0.9 wt% other actinides (via (n,g), (n,2n), b^-):
  - **0.8 wt% ^{239}Pu** (via ^{235}U nc, b^-), **^{240}Pu, ^{241}Pu**
  - 0.04 wt% ^{237}Np
  - 0.002 wt% ^{244}Cm
  - ^{241}Am, ^{243}Cm, ^{236}Np, (...)
- ~3.4 wt% **fission products** ($^{135,137}Cs$, ^{90}Sr, ^{129}I, ^{79}Se ...)
- metallic segregations, e-phase (^{99}Mo,^{99}Tc,^{105}Ru,^{105}Rh)

Photos (3): INE





Light microscope of irradiated UOx pellets with Zircalloy cladding

Radioactive waste – Vitrified waste

Composition of vitried waste – HLW

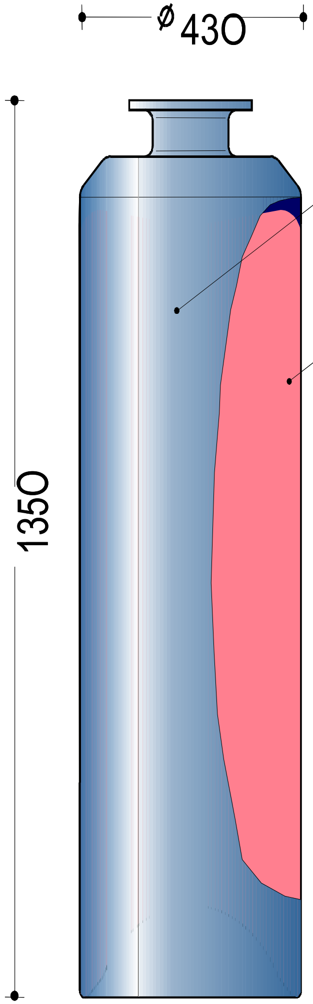
HLW-glass in thin walled stainless steel canister

Glass matrix SiO_2, B_2O_3, Na_2O
Process chemicals $NaNO_3$, P …
Corrosion products Fe, Cr, Ni …
Fission products Nd, Ce, Cs, Mo, Ba, Zr …

γ contact dose rate <400 Gy/h dominated by ^{137}Cs, ^{90}Sr
~$3*10^{15}$ Bq ^{137}Cs, ~$3*10^{15}$ Bq ^{90}Sr
actinides U (7 kg),
Am, Np, Pu (0.19 kg)

Total α activity 10^{14} Bq

Vitrified HLW (Karlsruhe)



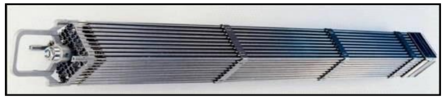
1 Ci = 3.7 10^{10} Bq

Storage & disposal

NPP

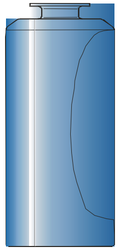
Irradiated

Nuclear fuel

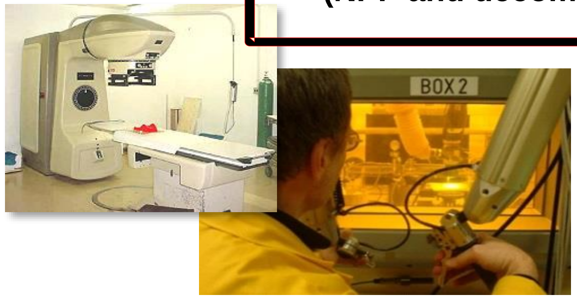


Waste from reprocessing **(i.e vitrified)**

Intermediate storage



(NPP and decommissioning)



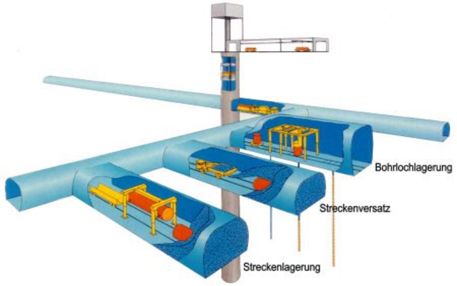
Negligible heat generation
(medicine, research, industry)

Intermediate storage

Repository for
heat generating radioactive waste

Repository for
radioactive waste with negligible heat generation

Final disposal
(deep geological + surface disposal

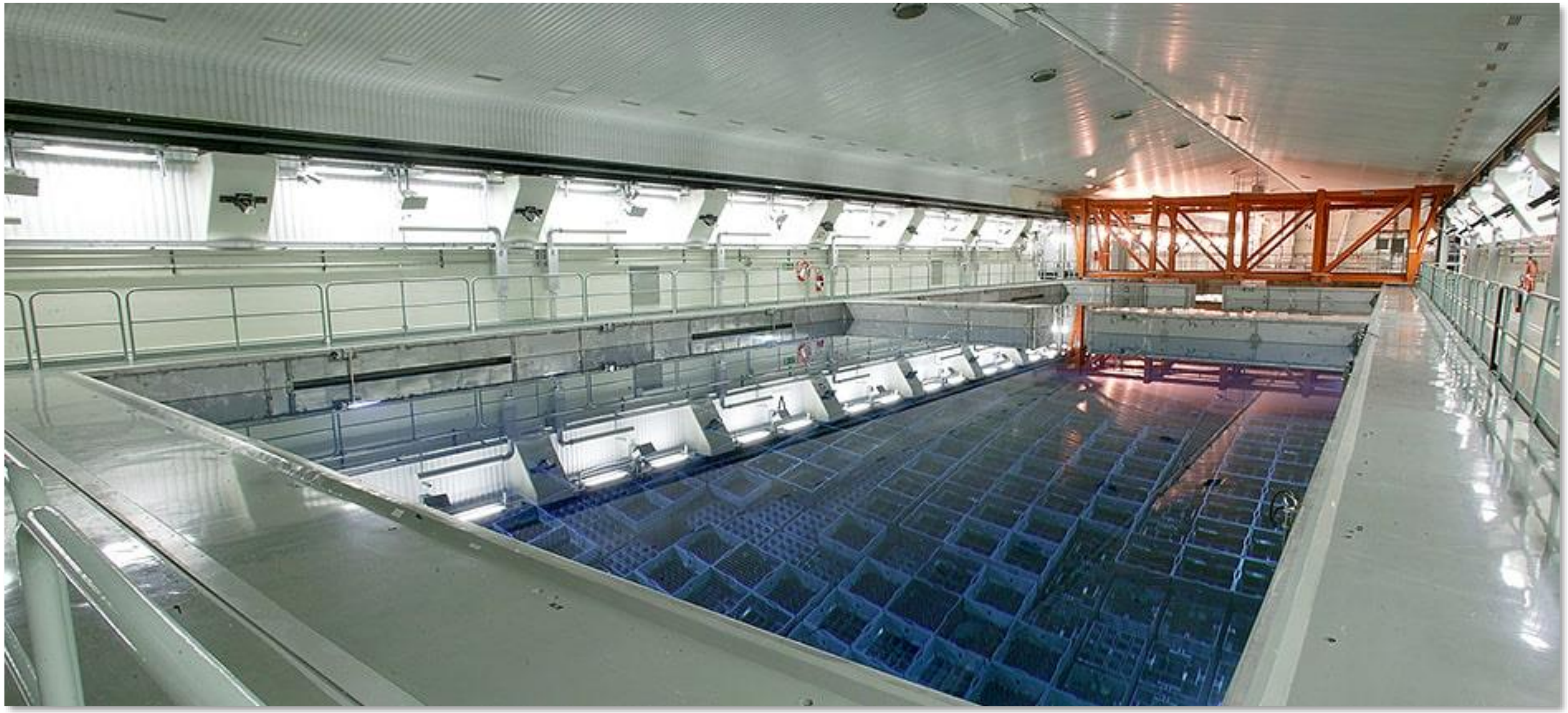


Heat generating radioactive waste

Negligible heat generation

Intermediate storage

Long-lived ILW-HLW - Interim storage-pools

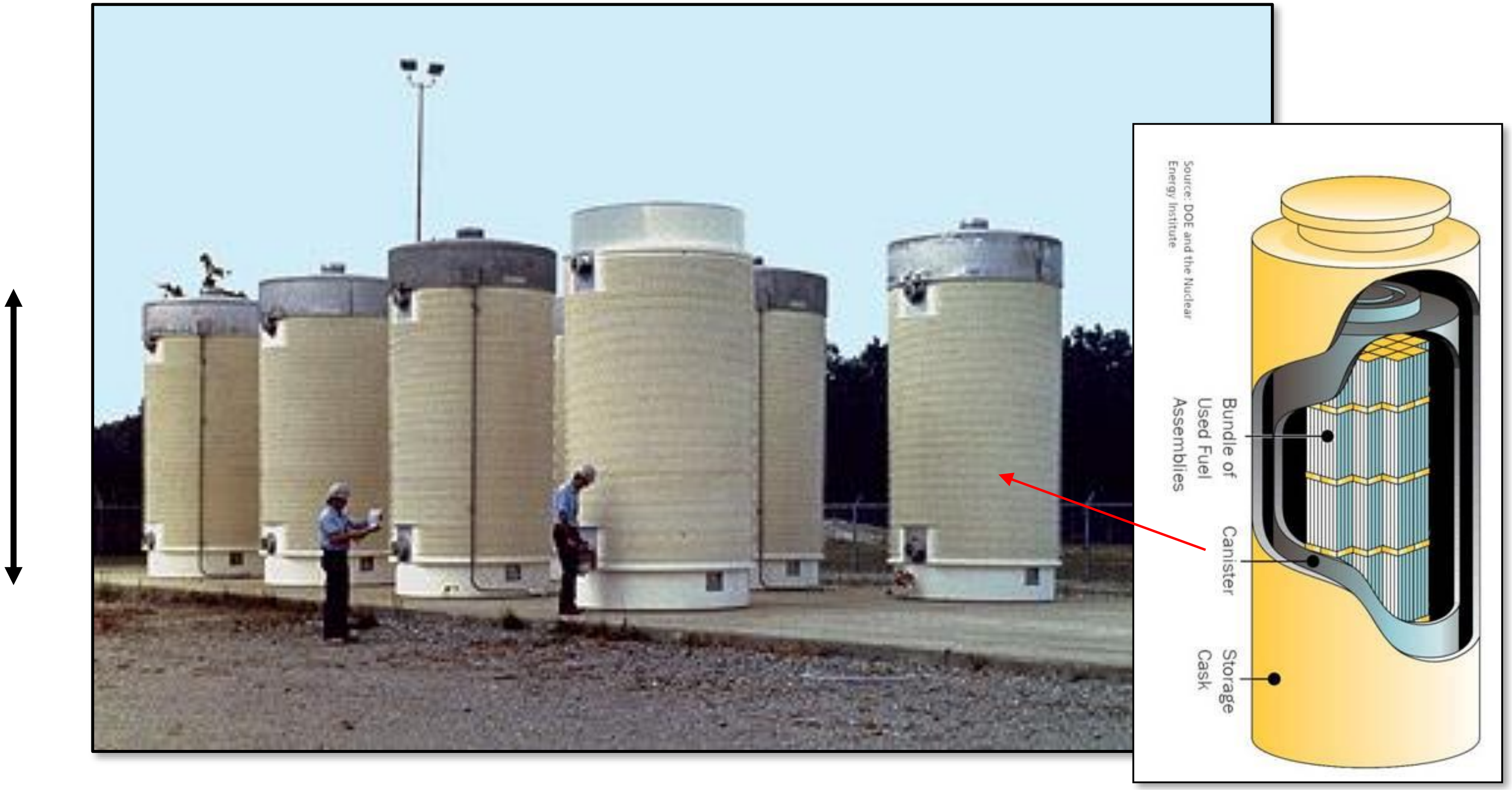


Spent Nuclear Fuel CLAB in Sweden (7-12 m Deep)

Intermediate storage

Long-lived ILW-HLW - Interim storage-dry cask

6 m



Intermediate storage

Long-lived ILW-HLW - Interim storage-dry cask

Zwilag´s ZZL (Switzerland)

Gorleben (Germany)

Intermediate storage

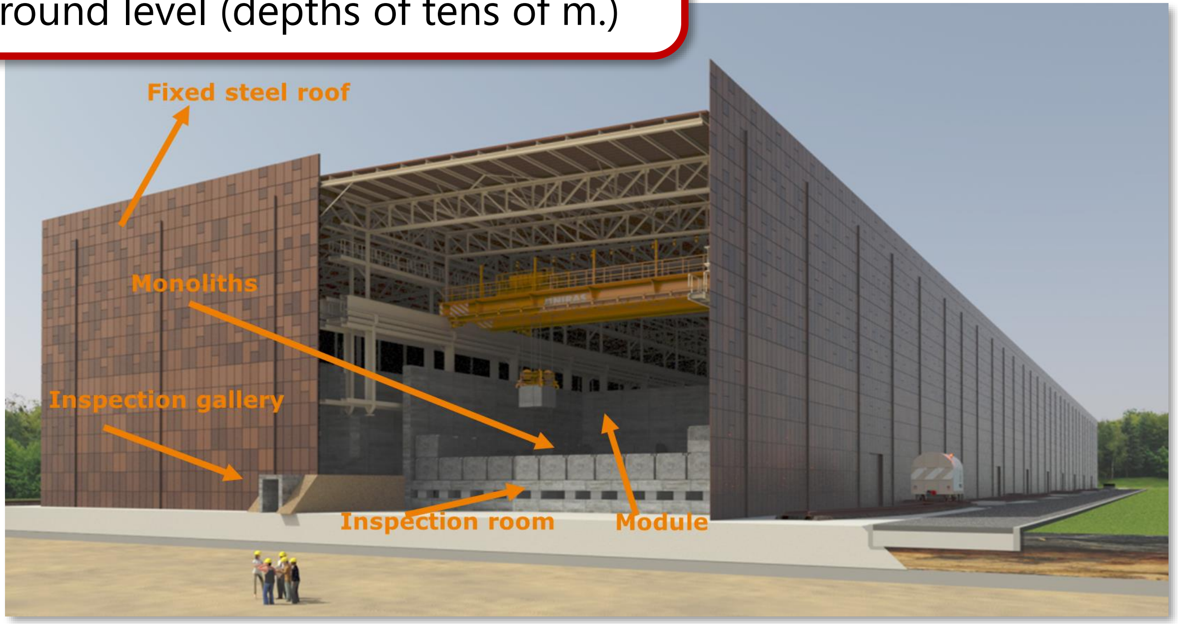
Long-lived ILW-HLW - Interim storage

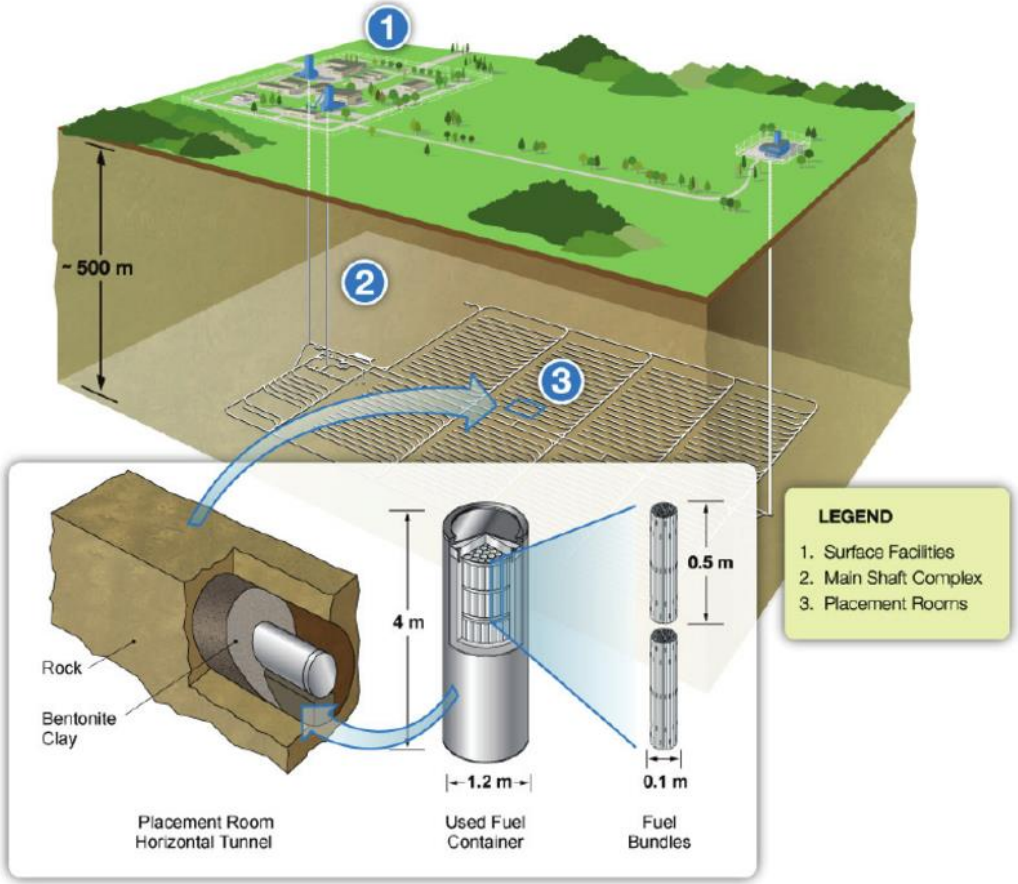
Belgoprocess (Belgium)

Würenlingen. (Switzerland)

Final disposal

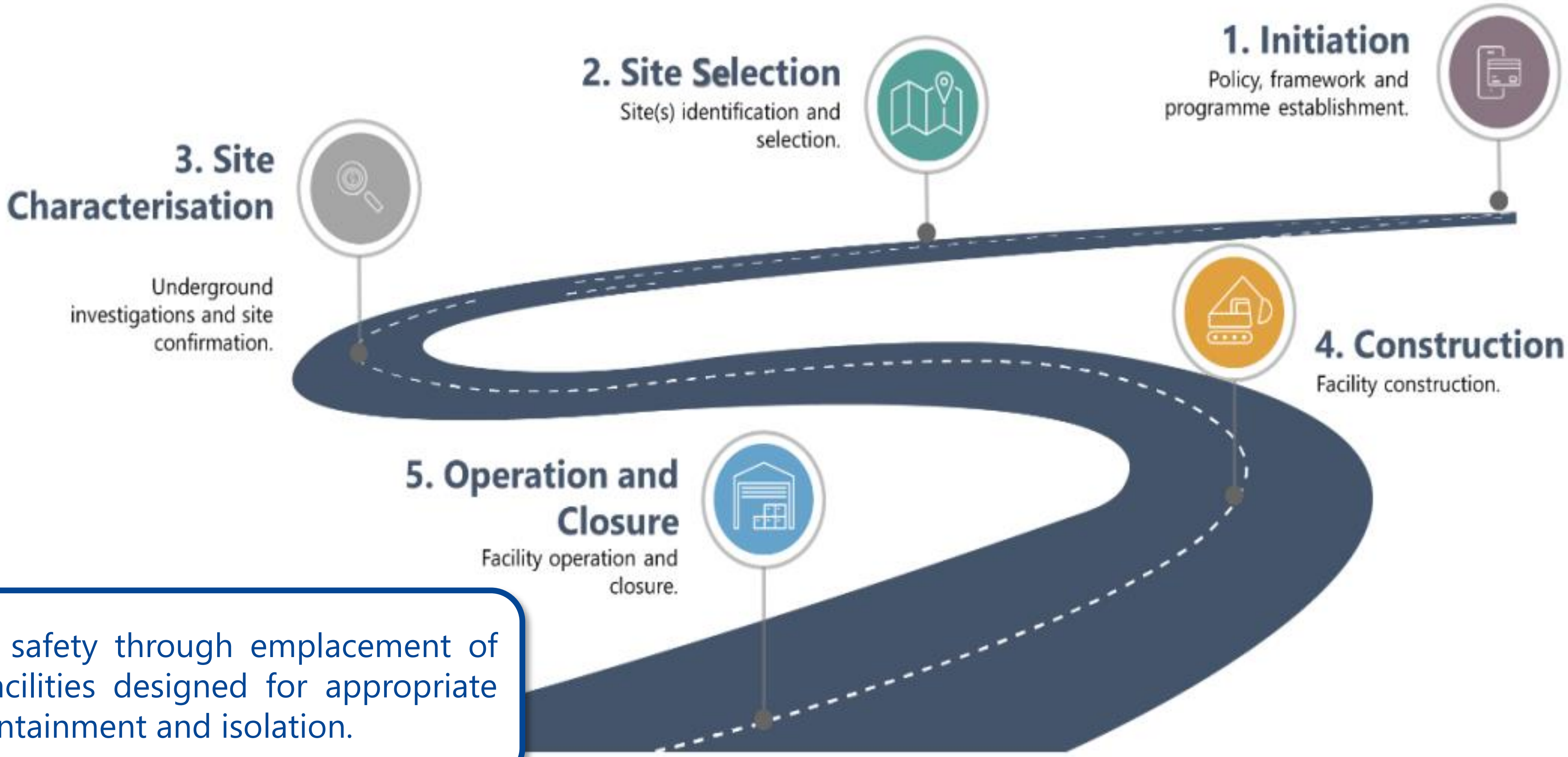
Near - Surface disposal
(at ground level, or caverns below ground level (depths of tens of m.)





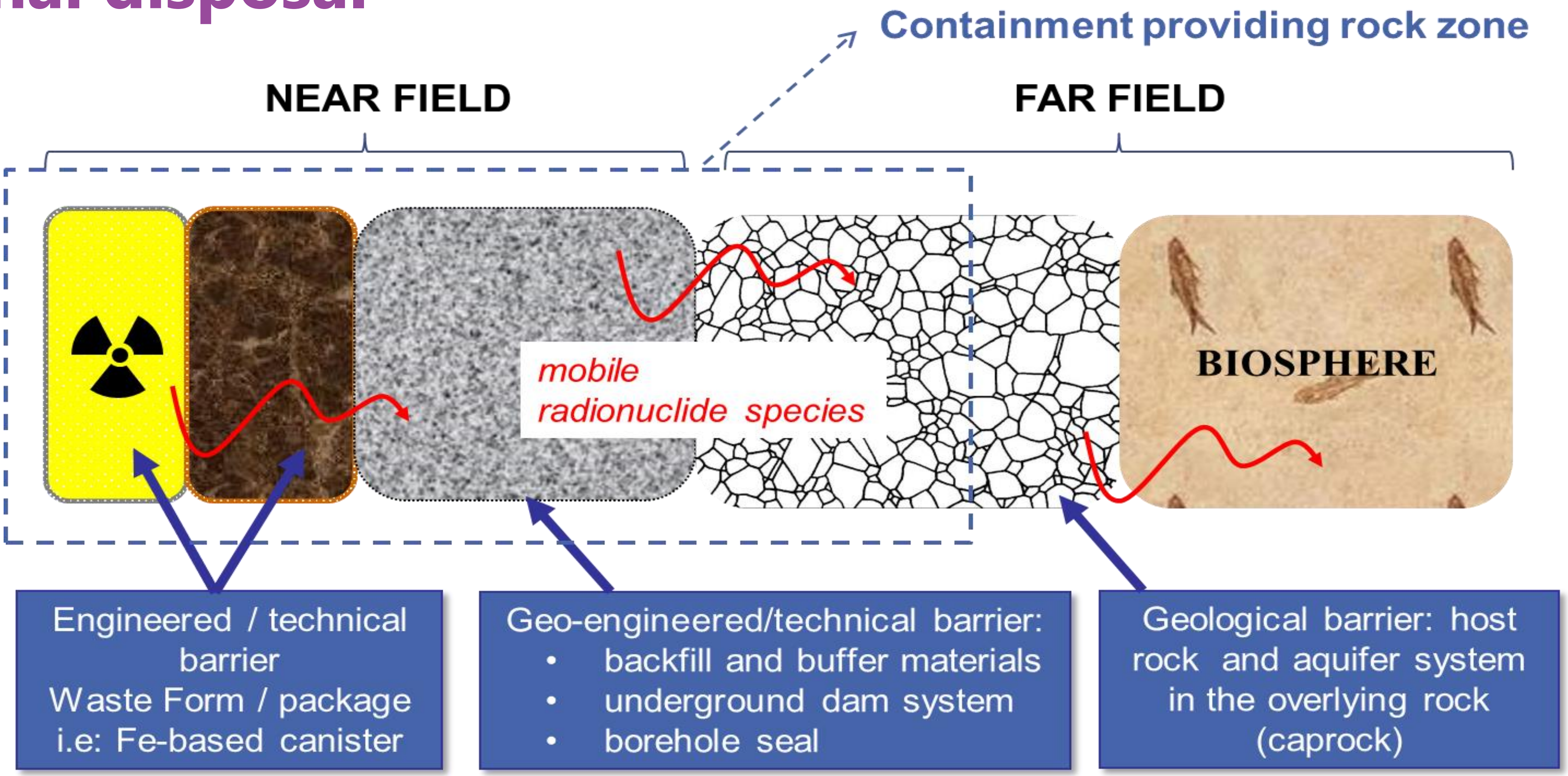
Deep geological disposal
(at depths between 250m and 1000m for mined repositories, or 2000m to 5000m for boreholes

Final disposal



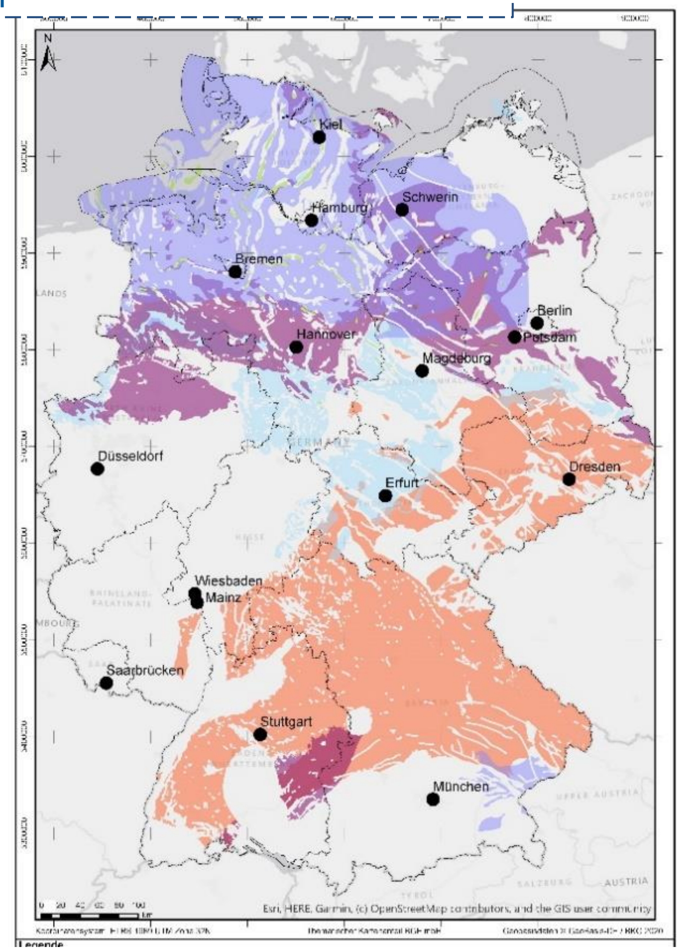
To provide safety through emplacement of waste in facilities designed for appropriate levels of containment and isolation.

Final disposal



Final disposal - host rock

September 2020 - Phase I



Rock properties

Heat conductivity

Temperature load

Permeability

Sorption capacity

Solubility

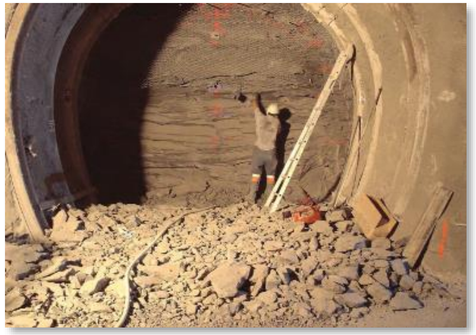
Plastic behaviour

Mechanic stability

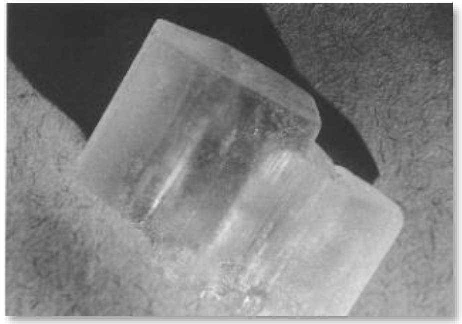
Excavation stability

Crystalline rock

Clay formations

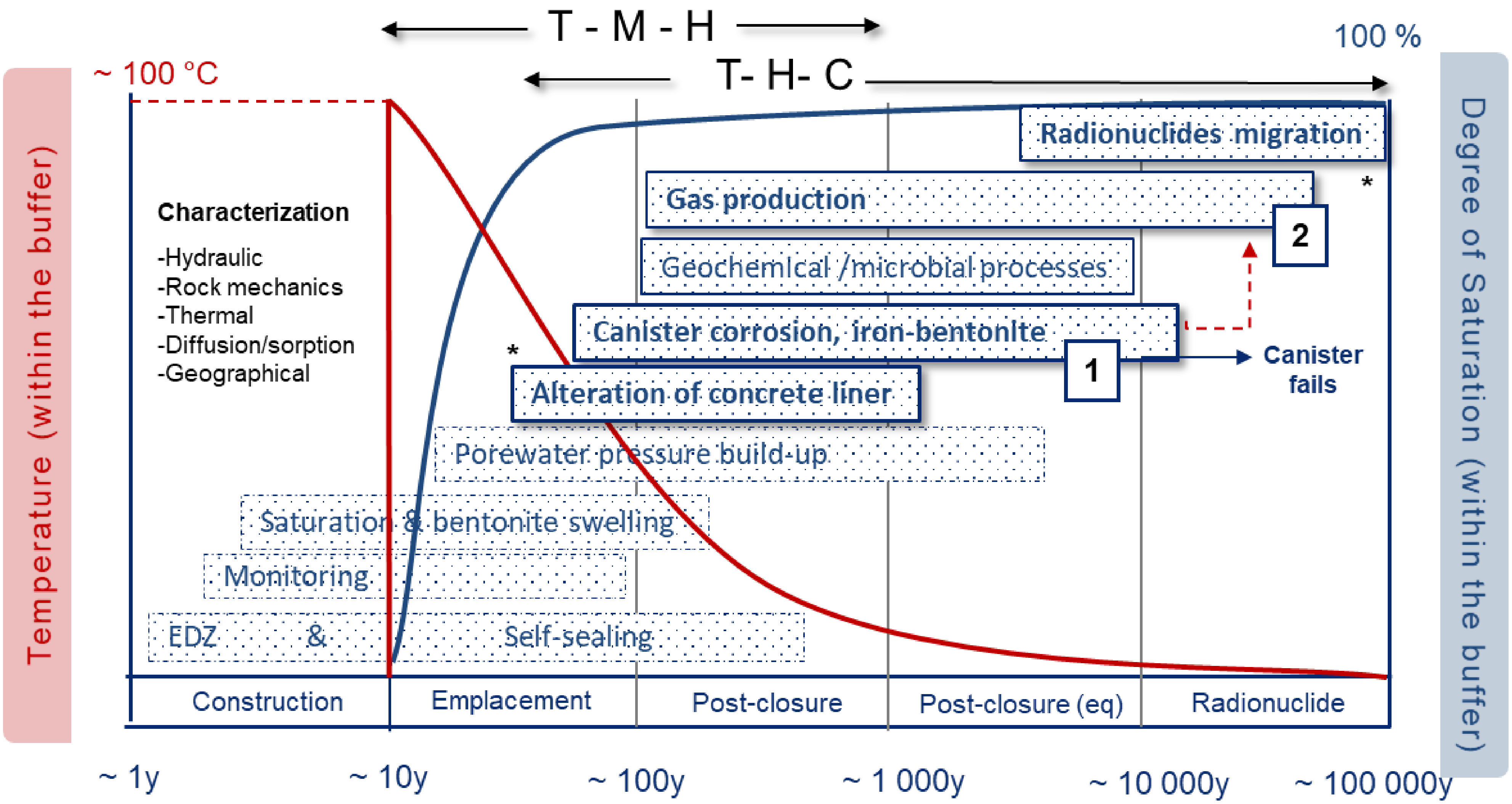


Salt domes

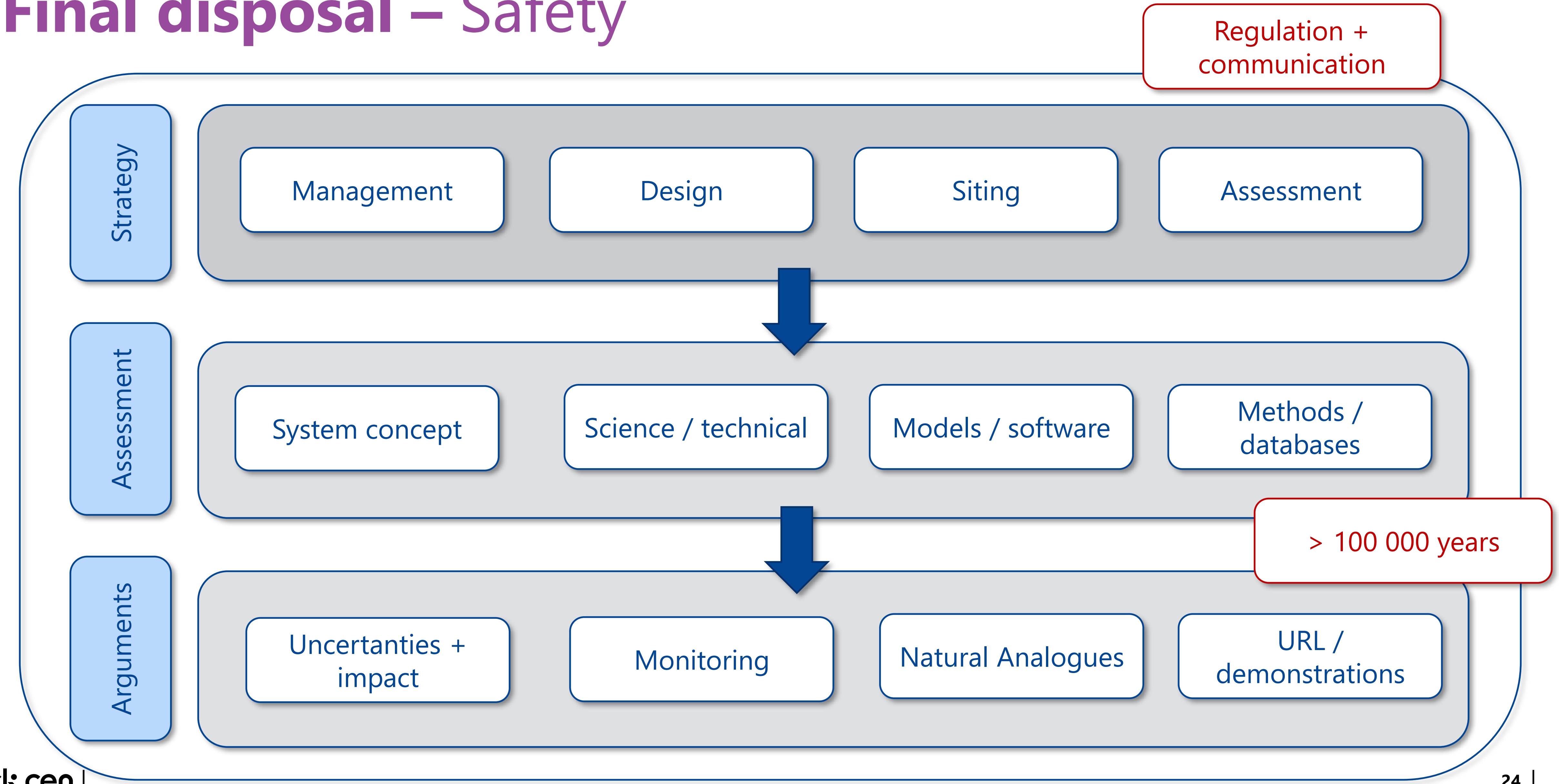


Geological Data Act (approved in June 2020)

Final disposal – processes & evolution



Final disposal – Safety



Final disposal options

Low level waste (LLW) - near surface disposal at ground level

LLW Drigg, Cumbria (NDA-UK)

LLW-ILW El Cabril (ENRESA-Spain)

LLW-ILW Aube (ANDRA - France)

LLW Rokkasho-Mura (JNFL-Japan)

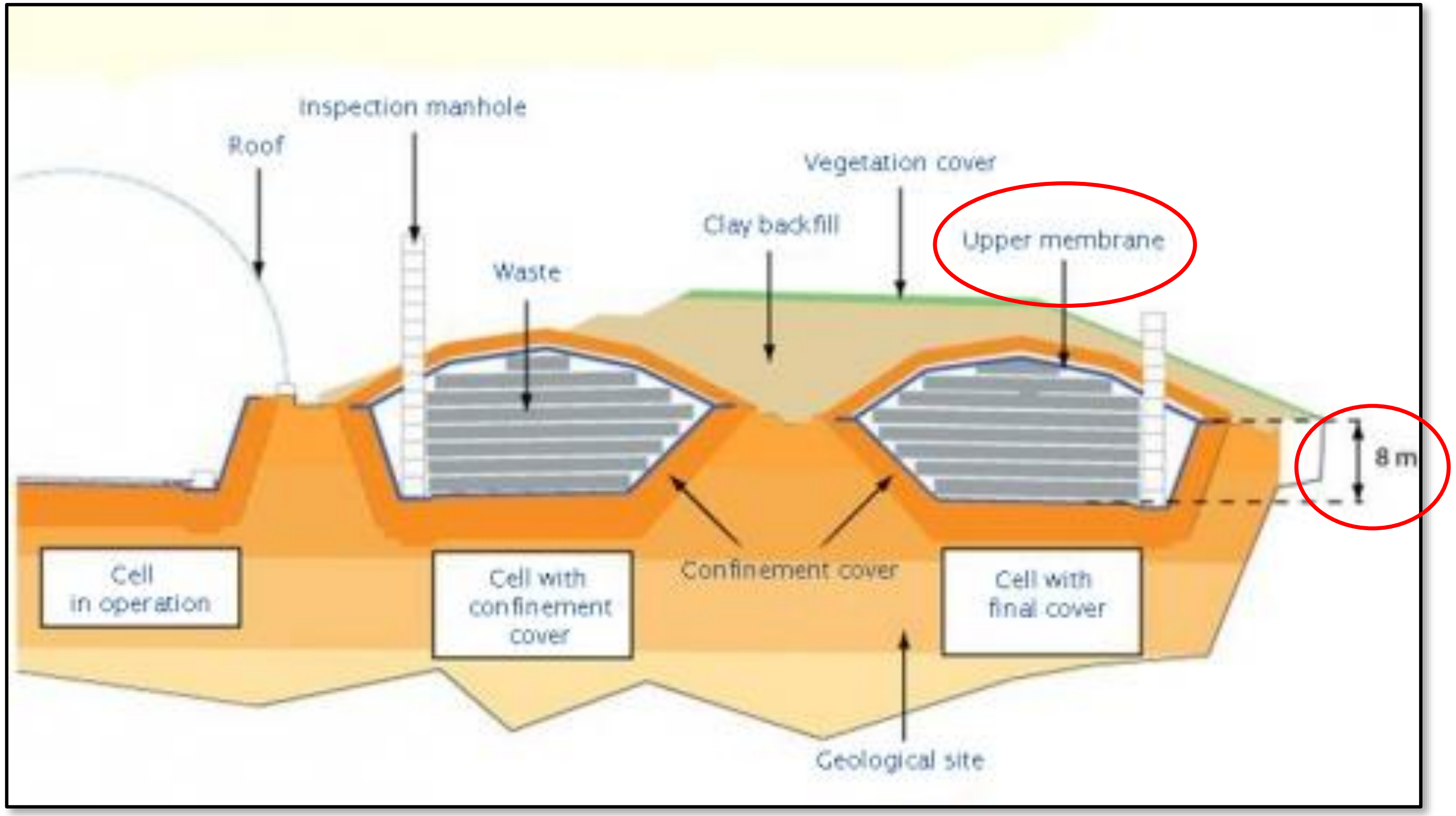
LLW Texas Compact (WCS-USA)

Most LLW is sent to land-based disposal immediately after its packaging for long-term management.

Majority of the waste (~90% v), a satisfactory disposal has been developed and is being implemented around the world.

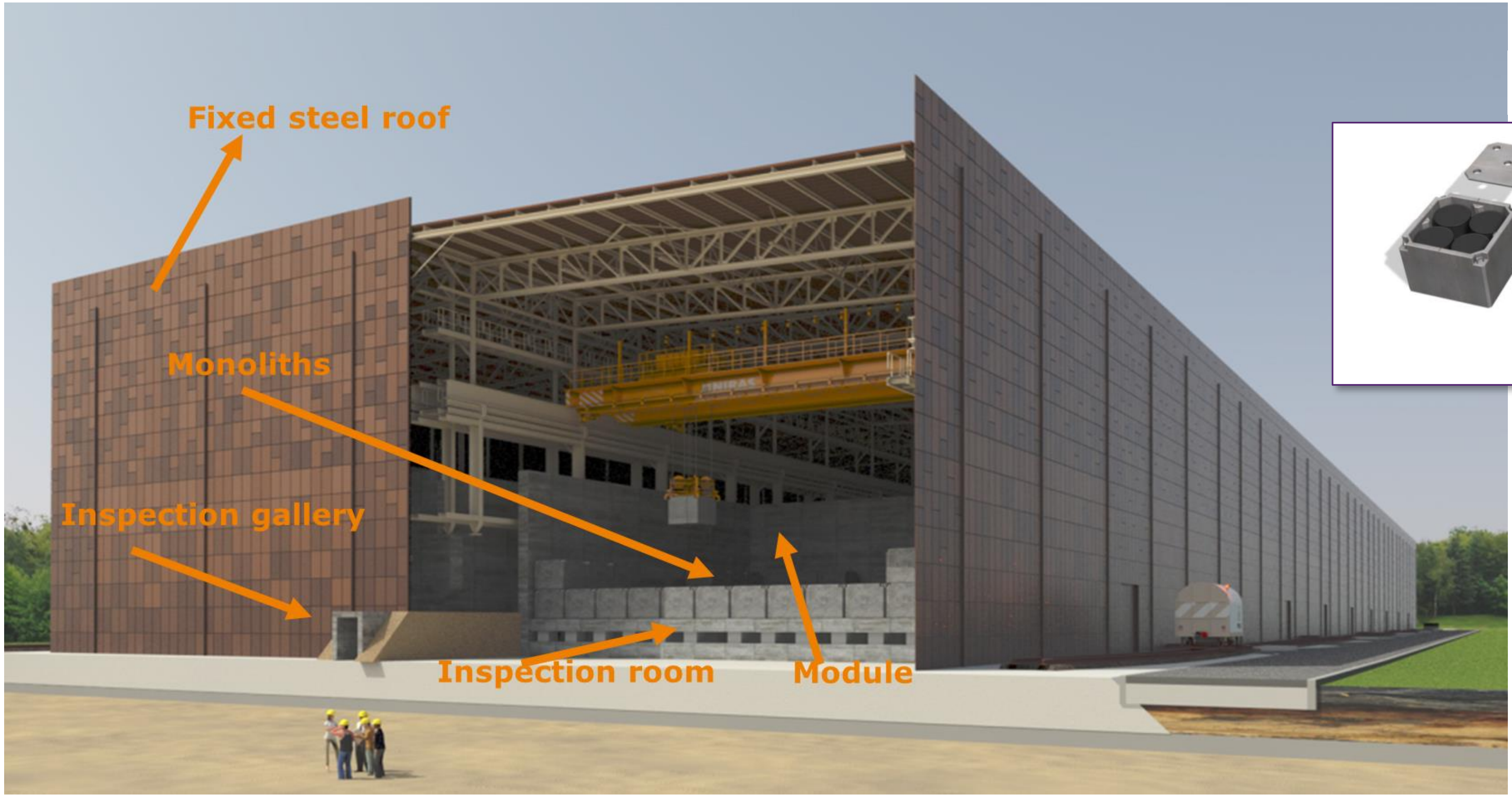
Final disposal options

Low level waste (LLW) - near surface disposal at ground level



Schematic diagram of a disposal cell (ANDRA-France)

Near Surface disposal – Dessel, Belgium



Concrete monoliths

**License 2023*

Final disposal

Low level waste (LLW) - near surface disposal below ground level

+ short-lived ILW radioactive waste

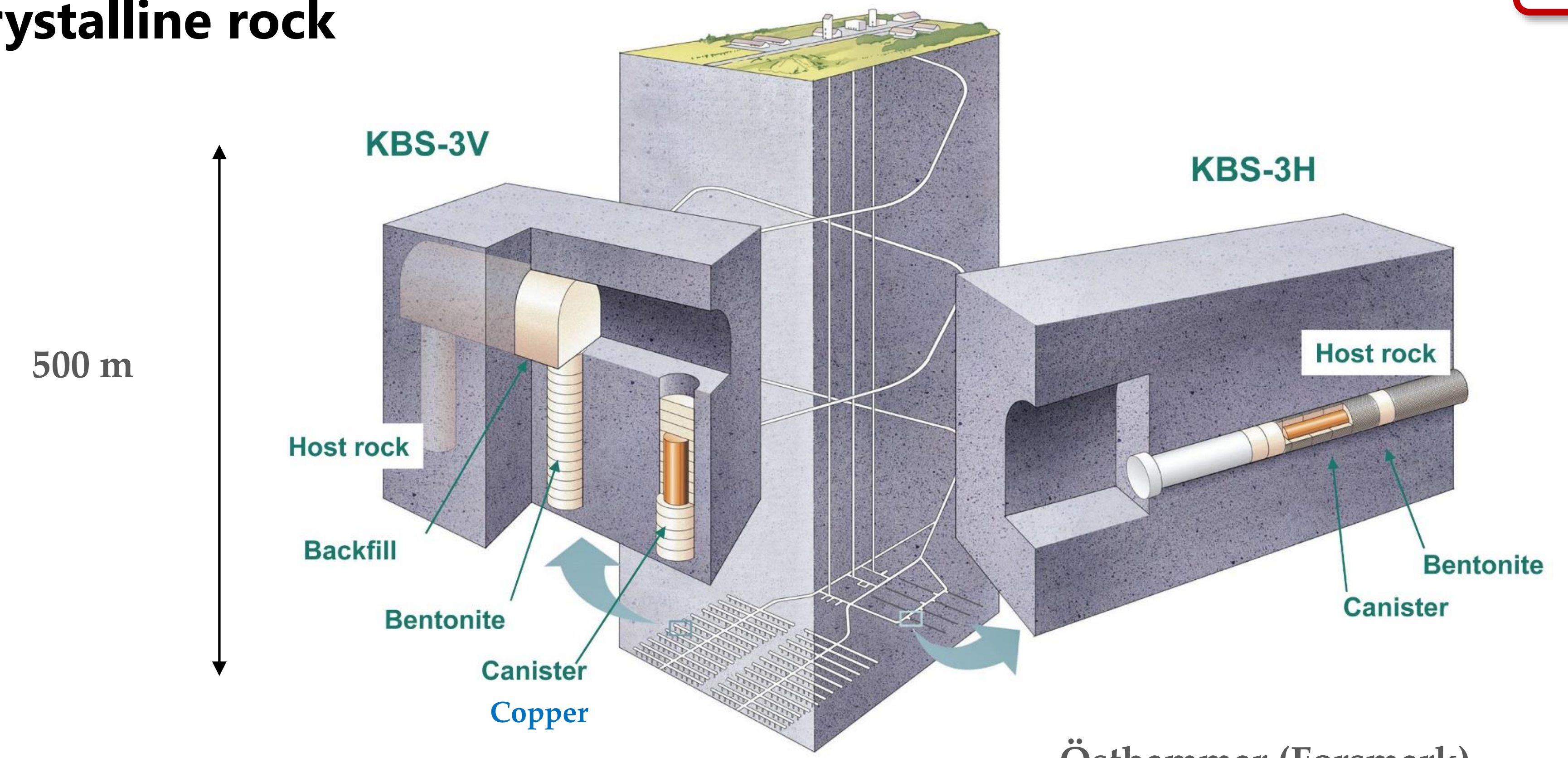
SFR, Forsmark (SKB-Sweden)

ISC: Restricted

Final disposal

1 000 000 years

Crystalline rock



Östhammar (Forsmark)

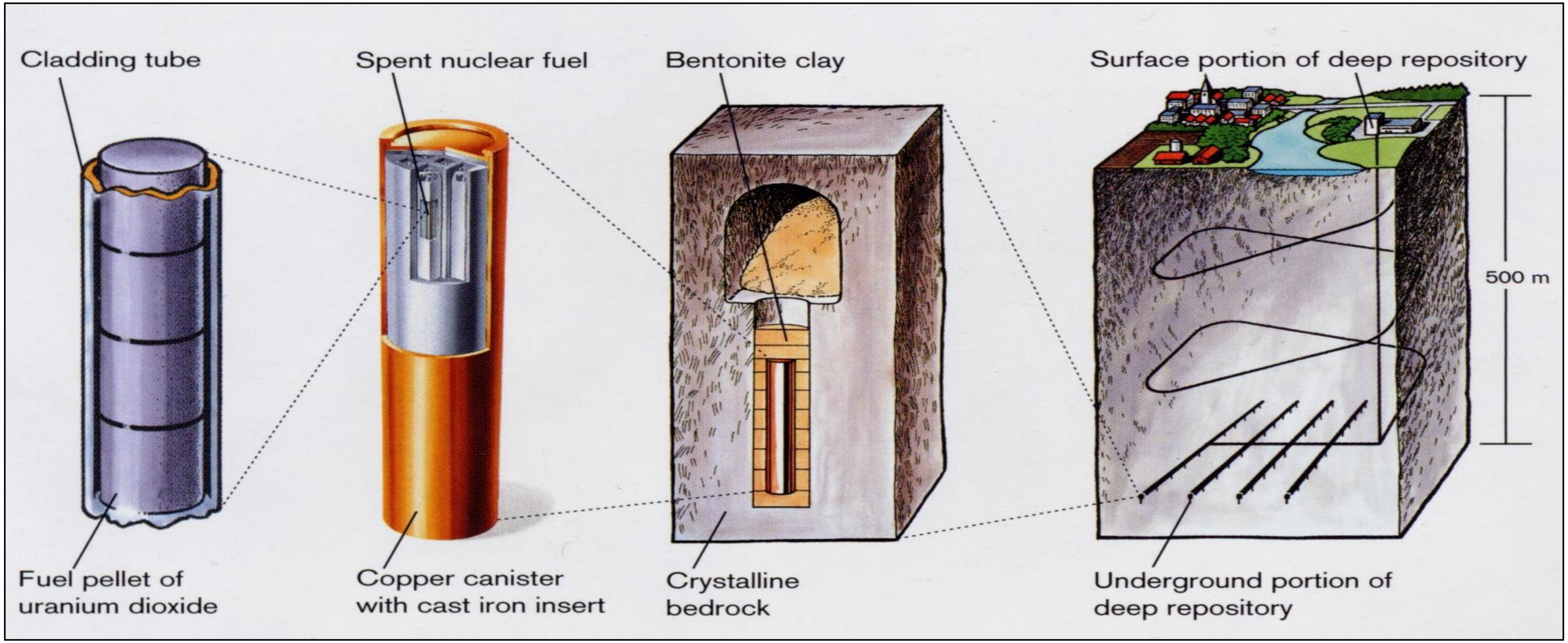
SKB (2006) Long-Term Safety for KBS-3 Repositories at Forsmark and Laxemar – A First Evaluation, Main Report of the SR-Can project, SKB TR 06-09, Swedish Nuclear Fuel and Waste Management Co., Stockholm; Hedin et al. (2007) NEA-RWM report, NEA No. 6362, Nuclear Energy Agency, Paris, pp 45-56

Final disposal

Engineered Barrier
- Spent fuel
- Copper Container

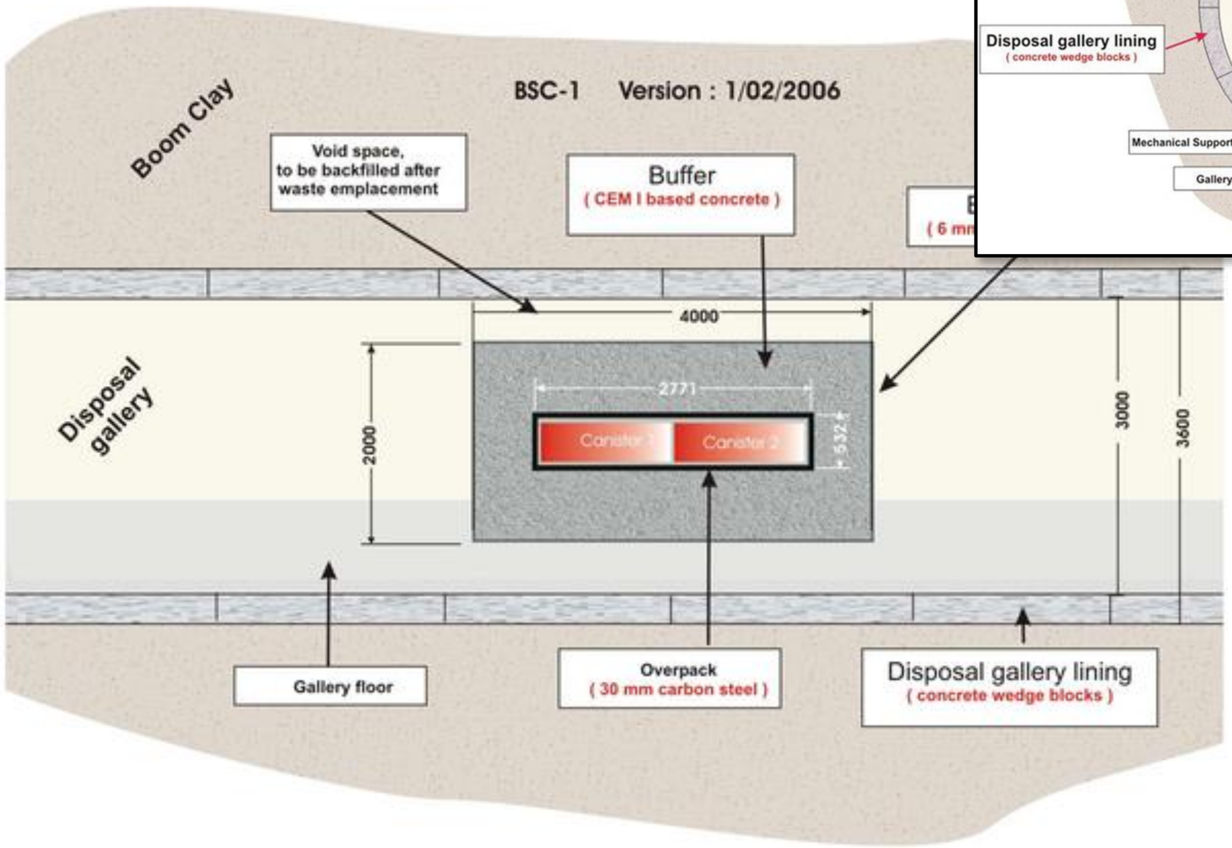
Geoengineered Barrier
- Drift backfill
- Underground dam systems
- Shaft and borehole seals

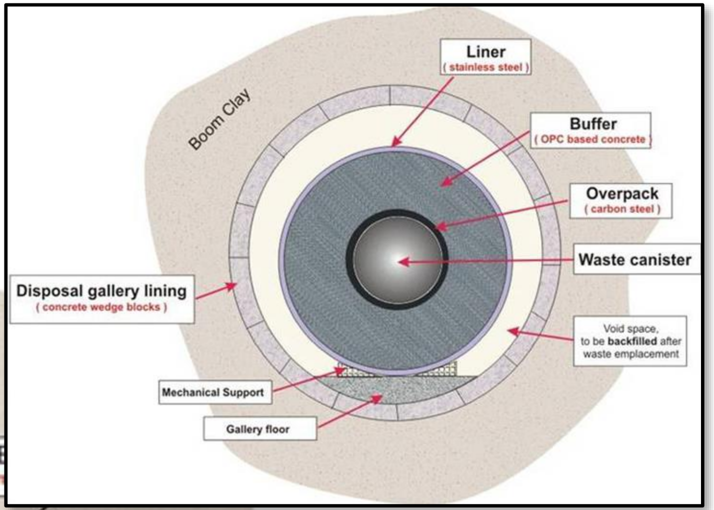
Geological Barrier
- Host rock (crystalline rock)
- Aquifer system in the overlying sediments



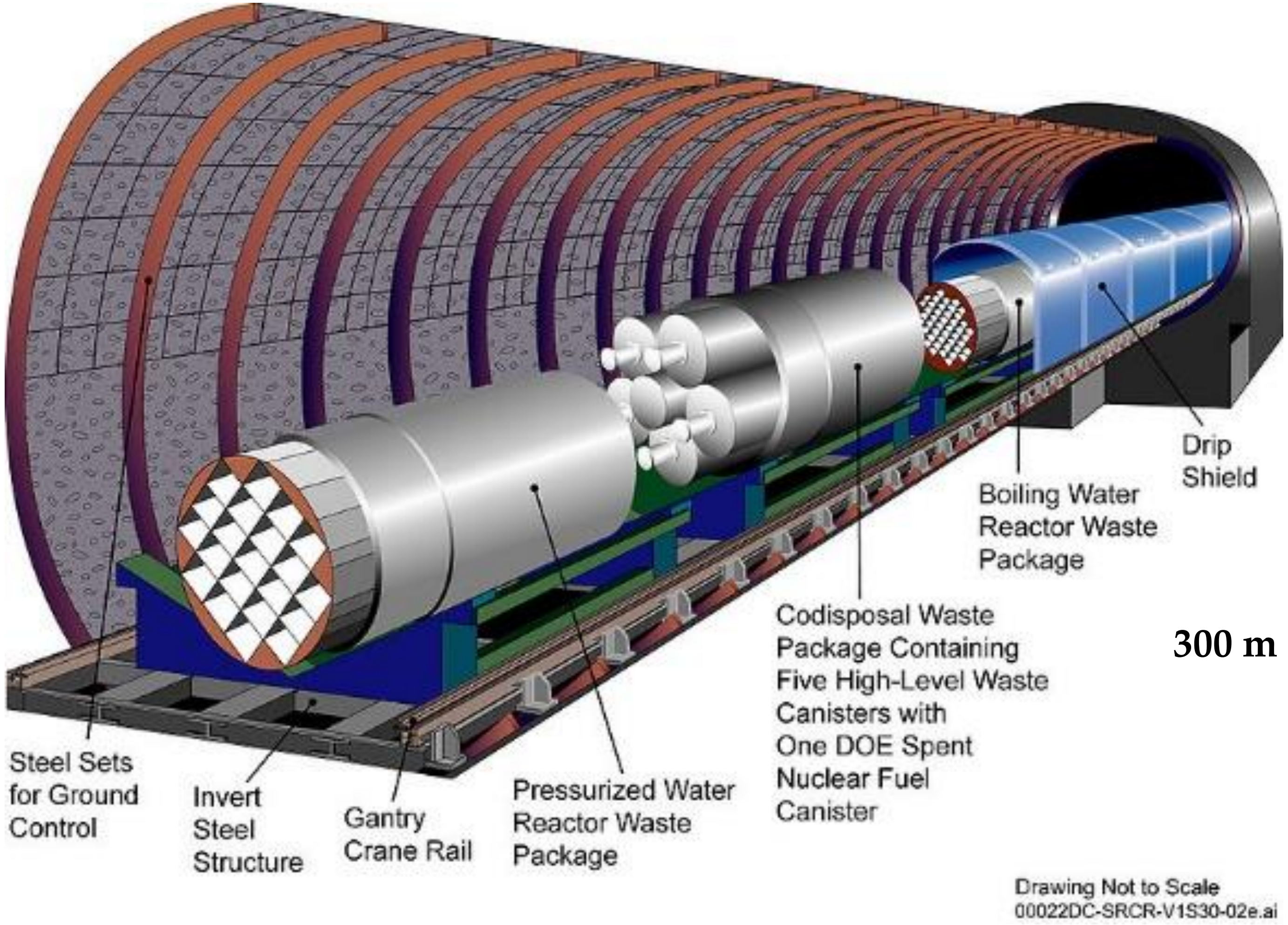
Final disposal

Clay rock





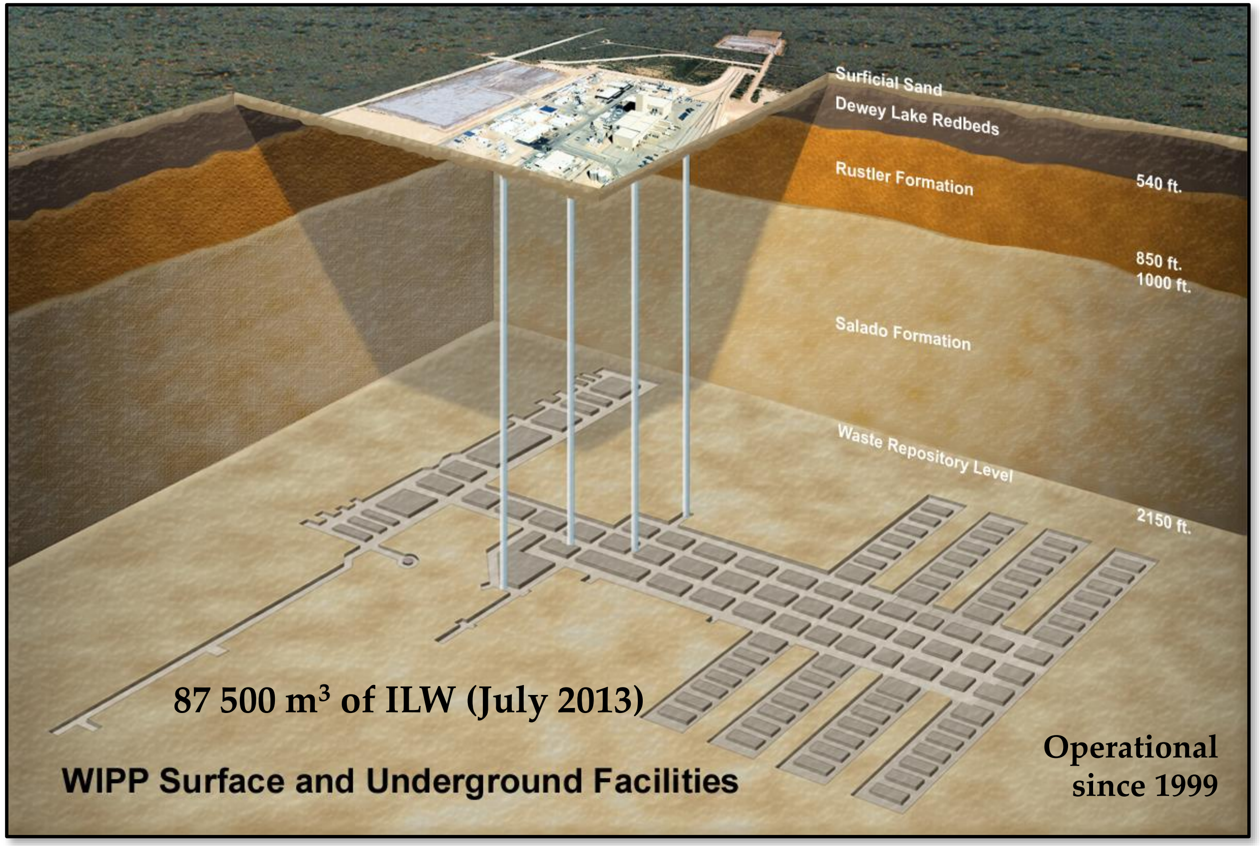
Final disposal



Tuff formation - USA have encountered political delays

300 m underground

Final disposal



650 m

Disposal facility for defence related transuranic waste LL-ILW (salt formation)

Final disposal - alternatives

Near surface

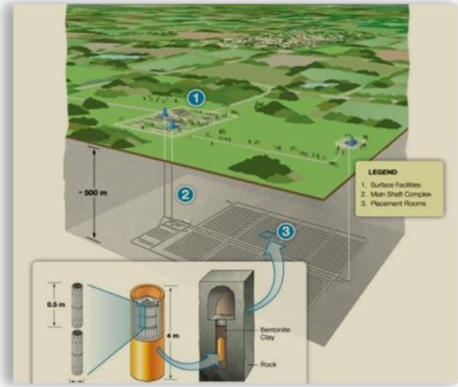
Ground level, LLW

Below ground level

Interim storage

ILW, HLW

Deep Geological



Final disposal

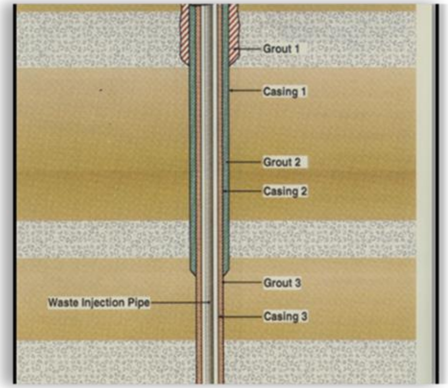
Tunnels (rock, salt, clay)

Deep boreholes

250 – 5000 m

Accepted

Alternatives



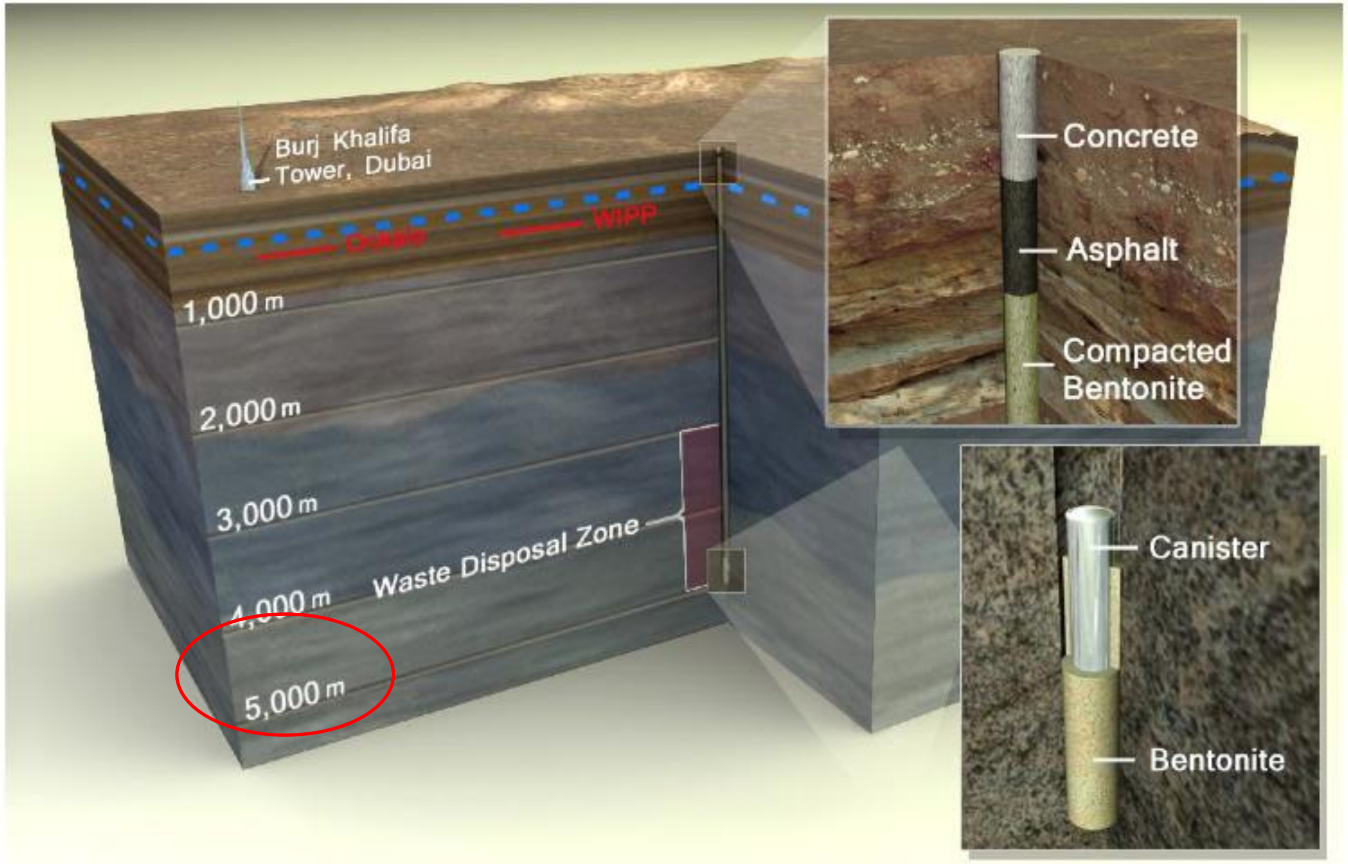
Rock melting

Sea disposal

Ice sheets

removal with spacecrafts out of orbit

Final disposal - alternatives

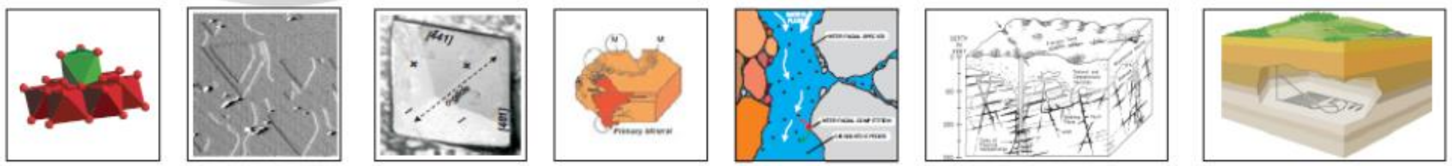


Waste not retrievable + more expensive

Science - Scales

Scales

Space



λ

1nm | 1µm | 10µm | 100µm | 1mm | 1m | 1km

Laboratory experiments

Underground research Laboratory

Natural Analogues

& Models....

Time

Days | *Weeks* | *Years* | *Decades* | *Milions of years*

Science – Multidisciplinary

Geology & seismology

Soil and groundwater geochemistry & mineralogy

Redox state, pH, ionic strength, cations & anions concentrations in water, organic colloids

Land use & hydrology

Cementitious materials

Waste packages & Backfill material

Meteorology & climate evolution

Aqueous radiochemistry & decay rates

Solubility & speciation

Lithological / hydro-geological characteristics

Ecology & Microbiol. processes

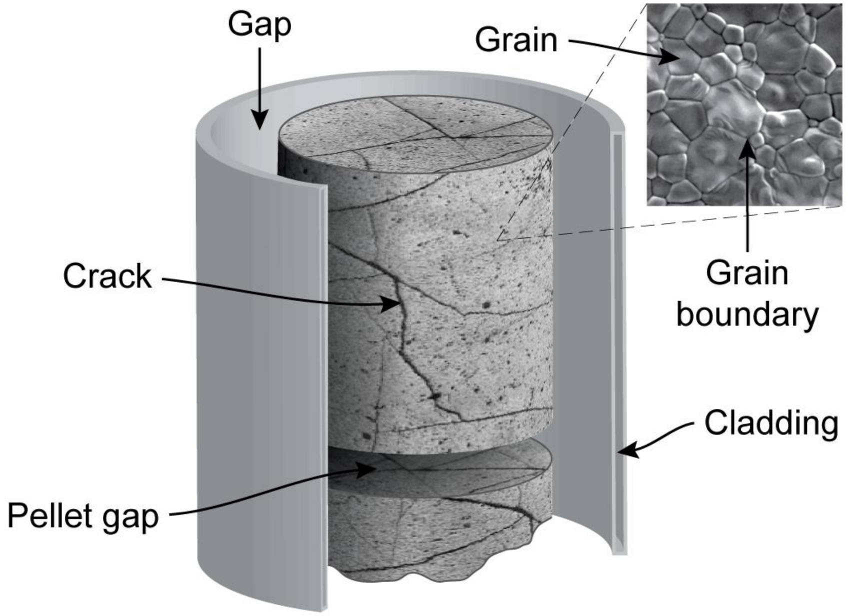
Mass balance between nuclides mobilization processes

Transport, sorption, ion-exchange, co-precipitation

Science – Spent Fuel

Spent Fuel dissolution

- IRF: **„instant" release** of labile fission products from gap and fractures (within months after solution contact)
- **Fast release** of **fission products** from **boundaries** of UO_2 grains
- Release of **activation products** from **cladding**
- Slow UO_2 **matrix dissolution** and consecutive release of uranium, Pu-239, Pu-240, Pu-241, Am-241, other **actinides as well as main inventory of fission products**



Carbol et al. (2012) Spent Fuel as Waste Material. In: Comprehensive Nuclear Materials (R.J.M. Konings, ed.). Elsevier

Science - Corrosion

Corrosion of the canister

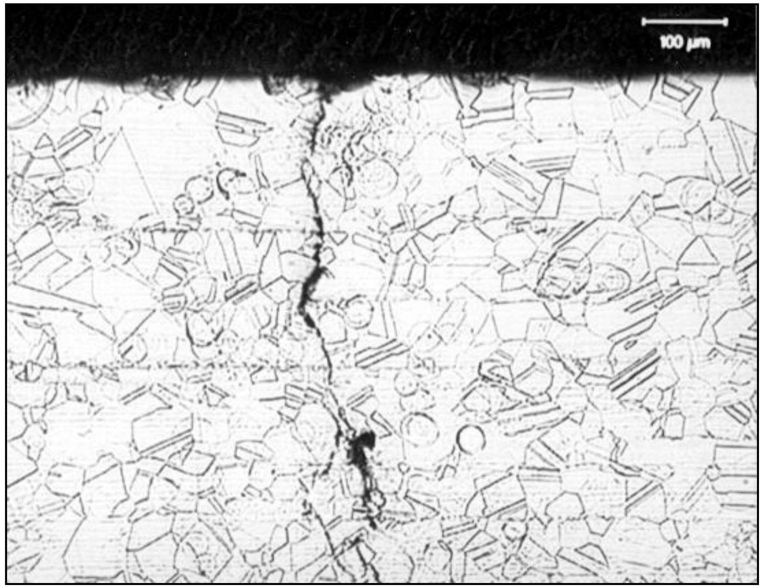
Oxidative **corrosion of Fe** based **container material** is the key process influencing radionuclide retention in the near-field

Failure of containers and water contact with the fuel assemblies are considered: corrosion rate < 10 µm/year in deep geolog. formation vs ≤ 1000 µm/year in oxic envir.)

Container, anaerobic Fe corrosion will produce H_2

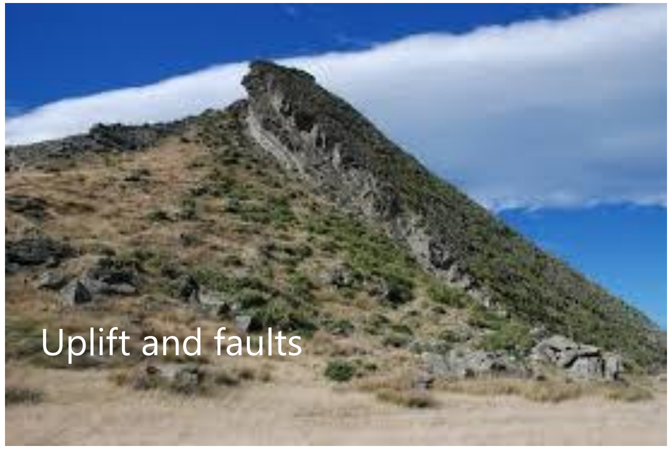
$Fe + 2H_2O \rightarrow Fe^{2+} + H_2 + 2OH^-$ // $3Fe + 4H_2O \rightarrow Fe_3O_4(s) + 4H_2$

H_2 remains dissolved at high concentrations (pH_2 > 40 bars) as long as the pressure built-up in the disposal site

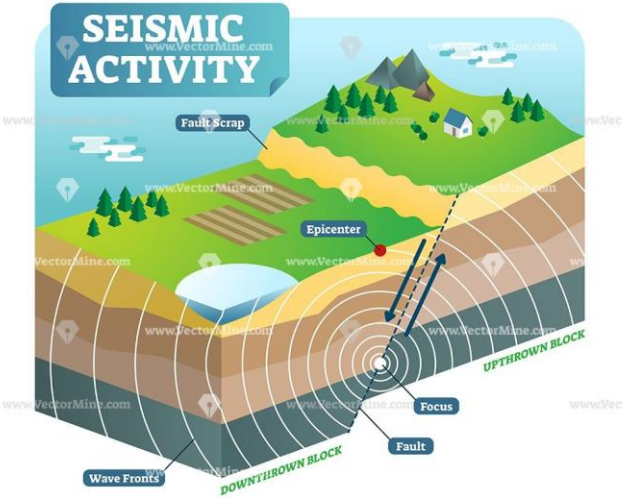


stress-corrosion cracking in stainless steel container: TSS-experiment at Asse II, 180°C, after 11 years

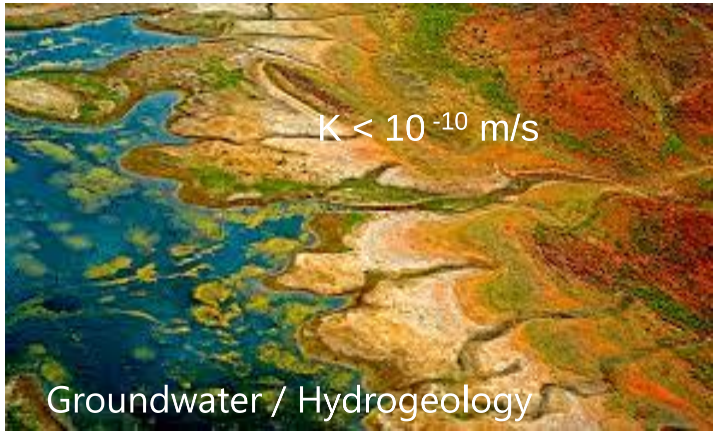
Science – Site characterization


Uplift and faults


Climate Change




Volcanism


$K < 10^{-10}$ m/s

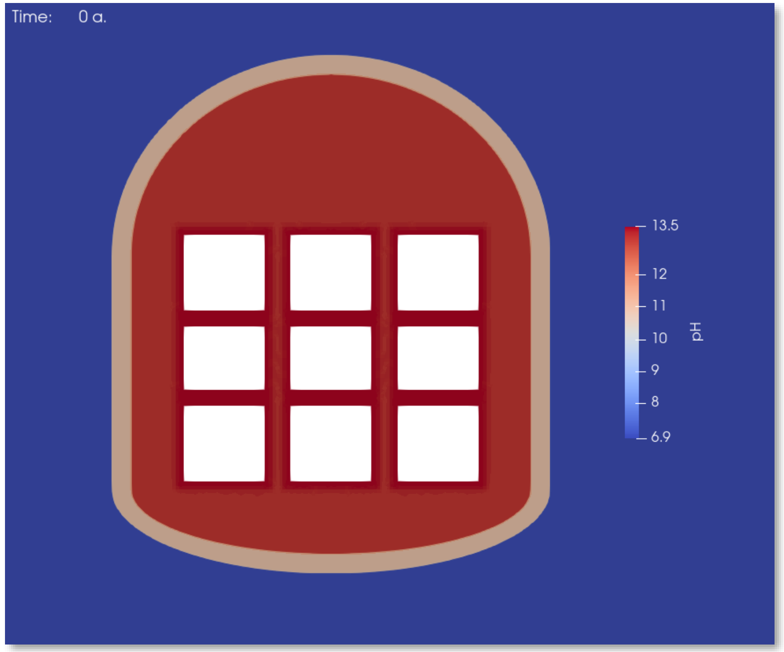
Groundwater / Hydrogeology


Mining – disturb systems

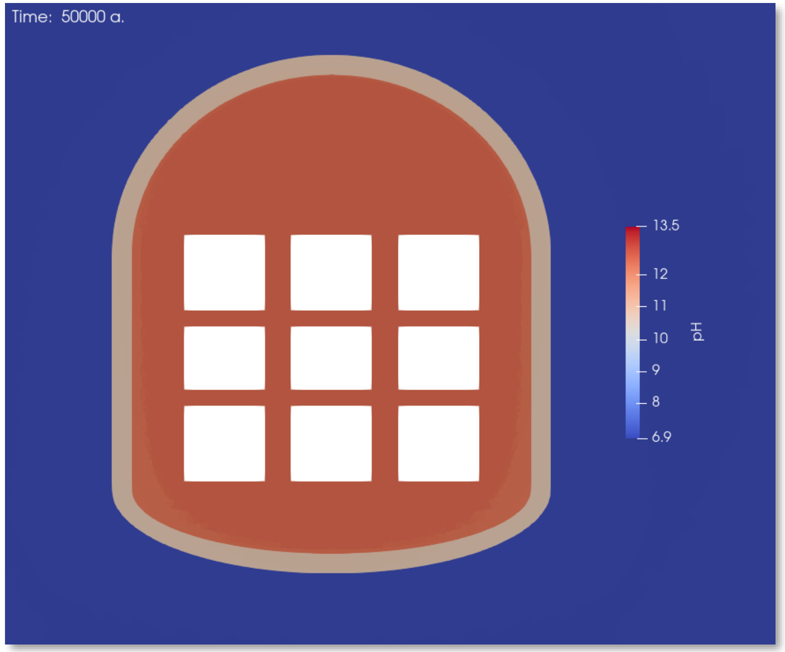
Science – Modelling

Evolution disposal cell in clay

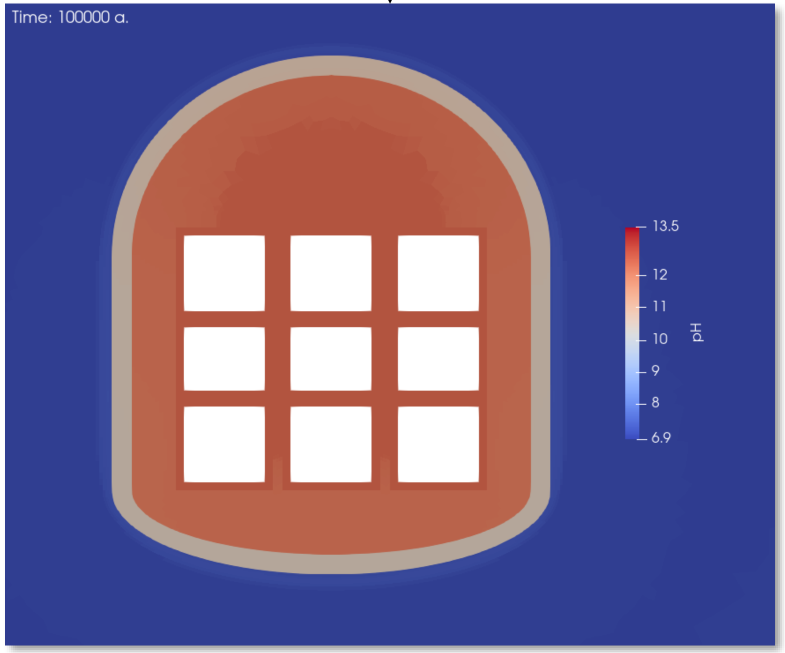
pH remains constant in clay rock after 100,000 years



Initial conditions



High pH of concrete walls and vault mortar stabilizes at ~ 12.5



Science – Undeground research laboratory

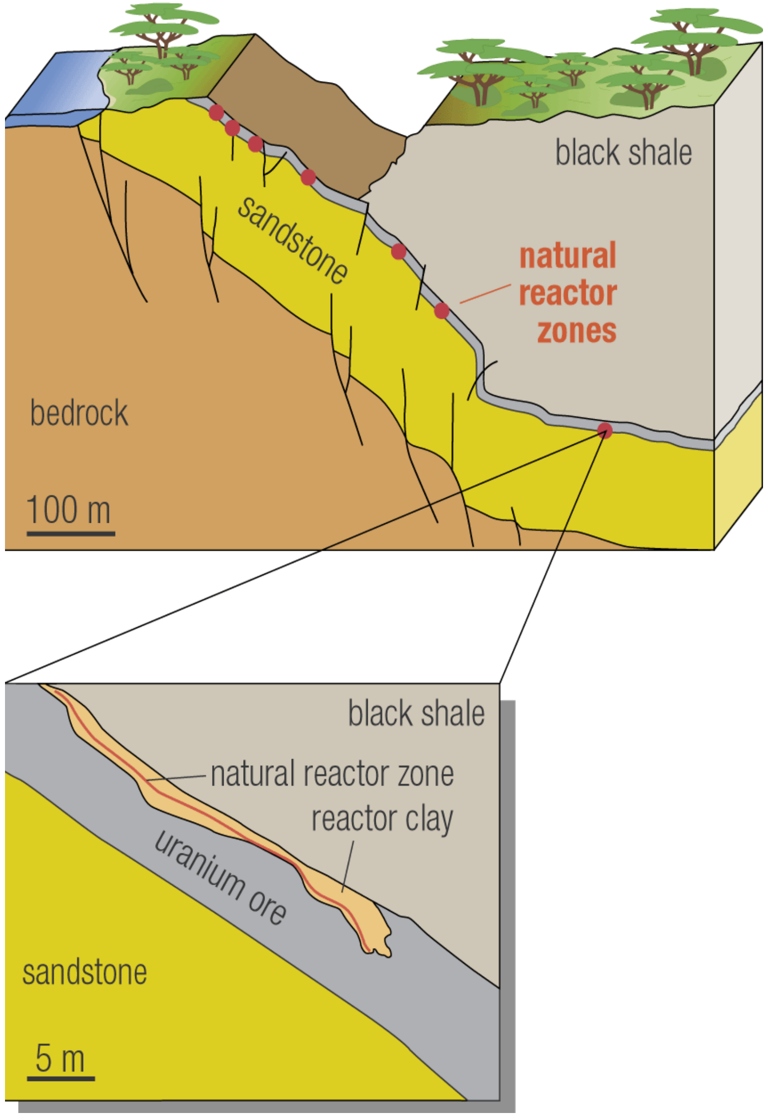
HADES, Mol, Belgium

225 m. **depth**

Natural Analogues

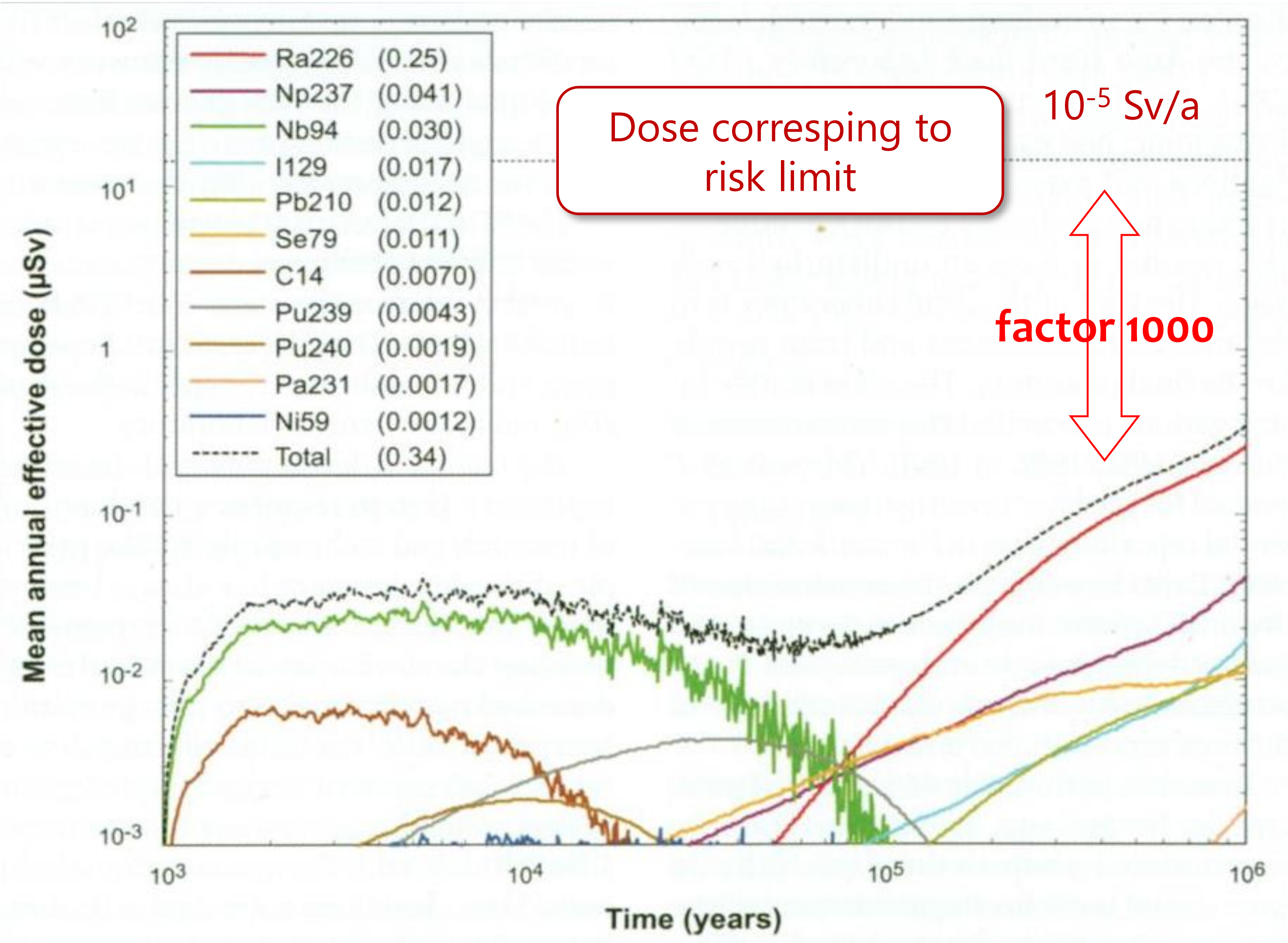
- **Less than 10% of uranium nuclides and other radionuclides migrated from natural reactor zone into surrounding rocks**
- Most of radionuclides and their decay products were confined in reactor zone, because of retention / incorporation in clay minerals, chlorite and apatite.

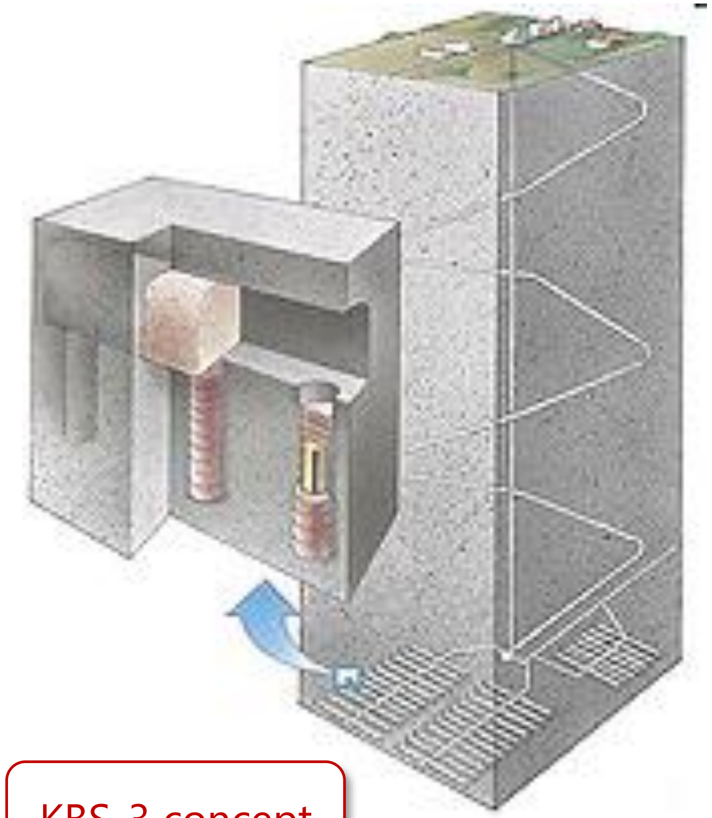
Oklo, Gabon: 1.8 billion years ago, uranium (235U ~ 3.5 wt%) was mobilised and accumulated at a geological confining layer in sufficient mass to achieve criticality



L. Duro & J. Bruno. (2012) in C. Poinssot & H. Geckeis, Woodhead Publ. Ser. in Energy; Andreas Gautschi (Nagra)

Safety Case - Calculations





KBS-3 concept

Long term safety analysis „SR-Site 2012" for disposal of spent nuclear fuel according to concept KBS-3 at the Forsmark site **(Sweden)**

EURAD

European Joint Programme on Radioactive Waste Management

eurad
European Joint Programme on Radioactive Waste Management

[Homepage | Eurad (ejp-eurad.eu)](https://ejp-eurad.eu)

Project Information

EURAD
Grant agreement ID: 847593

DOI
10.3030/847593

Start date	End date
1 June 2019	31 May 2024

Governance Roles:
- Bureau of the GA
- EuradSciences (RE college)
- WP leaders
- Task leaders

eurad science

Funded under
Euratom

Overall budget
€ 61 411 442,89

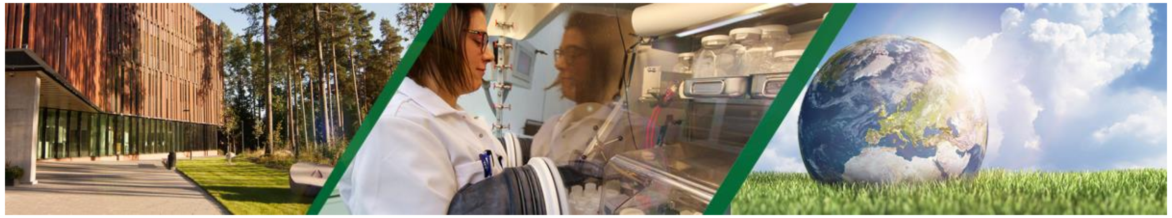
EU contribution
€ 32 500 000,00

Coordinated by
AGENCE NATIONALE POUR LA GESTION DES DECHETS RADIOACTIFS
France

EURAD Final event
22^{nd} – 25^{th} April 2024
Bucharest, Romania

→ **13 WP** (10 R&D, 2 Sts and KM)
→ Interaction Civil Society

EURAD – 2 (from fall 2024)



PREDIS

Project Information

PREDIS

Grant agreement ID: 945098

DOI

10.3030/945098

Start date

1 September 2020

End date

31 August 2024

Funded under

Euratom

Overall budget

€ 23 743 742,75

EU contribution

€ 14 000 000,00

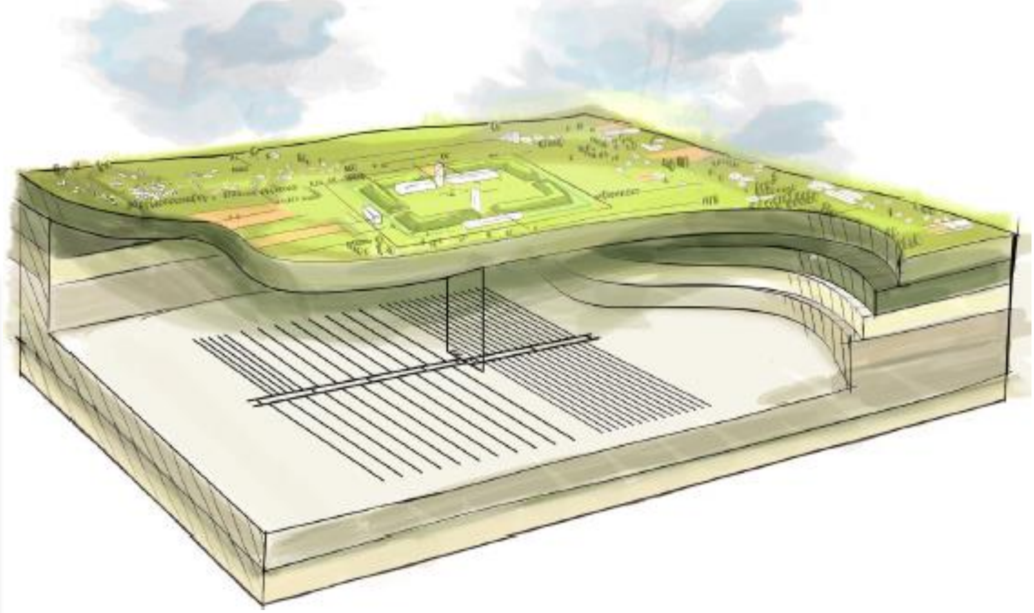
Coordinated by

TEKNOLOGIAN TUTKIMUSKESKUS VTT OY

Finland

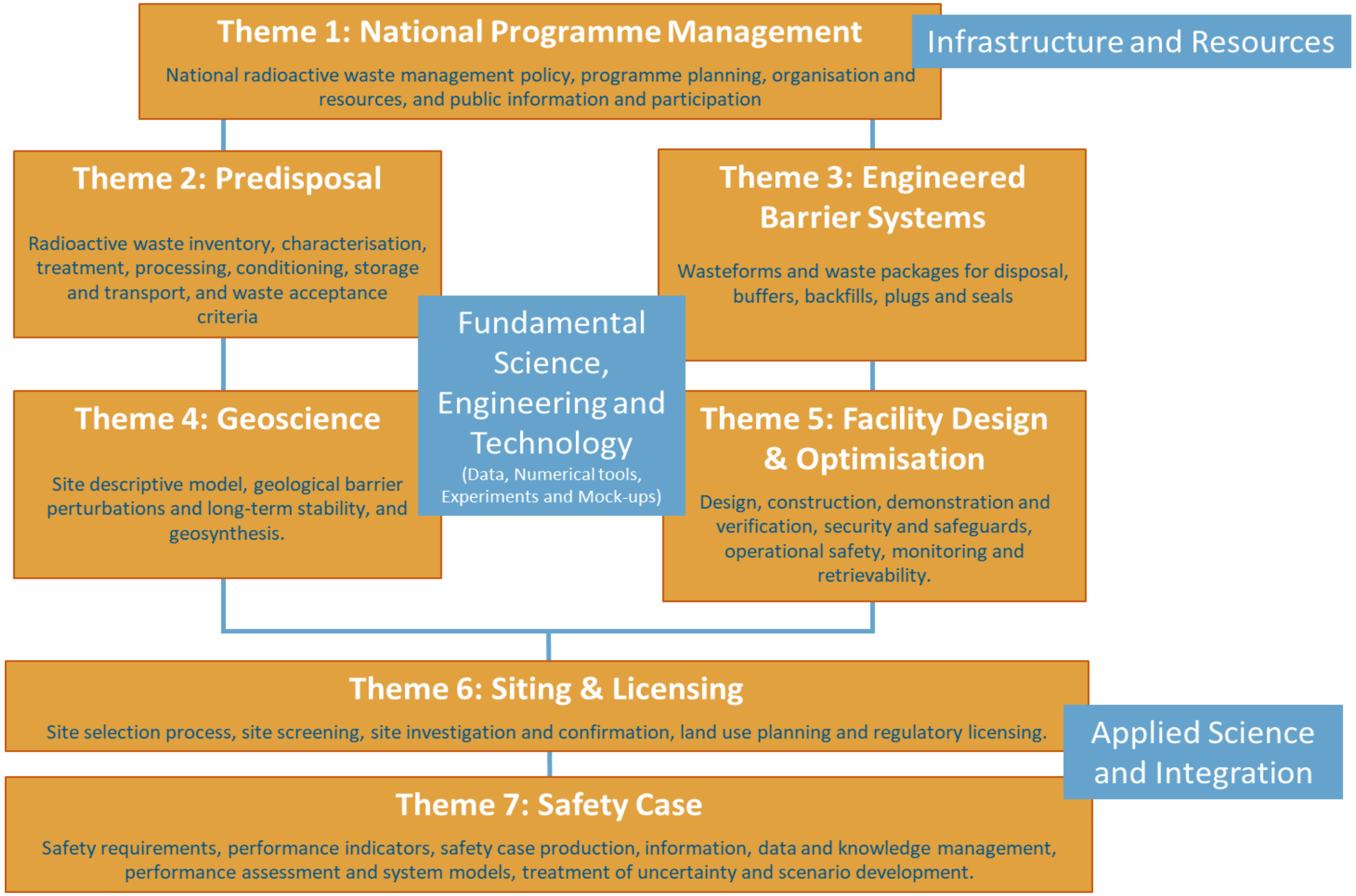
eurad

European Joint Programme on Radioactive Waste Management



The EC has established a Grant to Beneficiaries for a co-funded European partnership on **radioactive waste management**. This partnership aims for the continuation and merge of the current ongoing **EURAD** programme and **PREDIS** project.

EURAD – 2
Strategic Research Agenda (SRA) - Themes

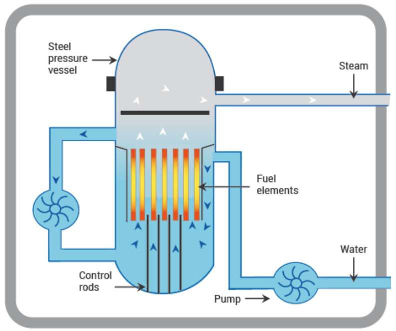


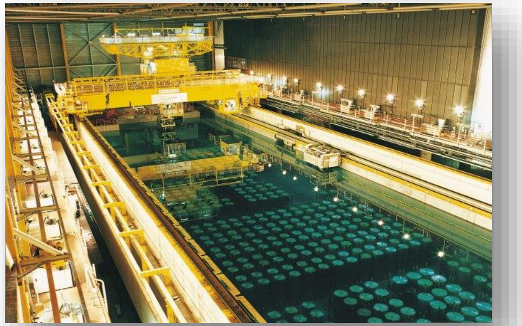
Sustainable waste management

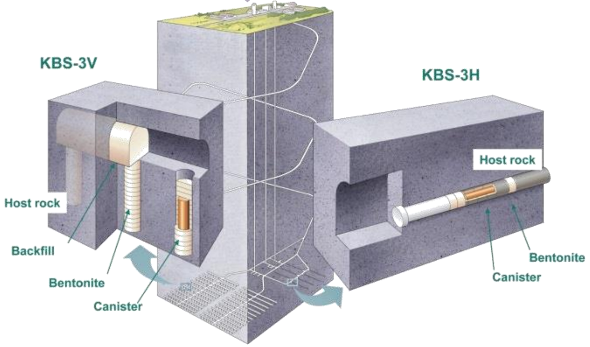
What is your interest?

What have we learnt?

Waste generation	Interim storage	Final disposal







Time limit

No -Time limit

Waste generation

Nuclear industry
Research
….

HLW

LLW/ILW

Clay
Crystalline
Salt

Steps to be followed:

Research → **Site exploration** → **Site selection** → **Long term safety**

Thank you very much for your attention

vanessa.montoya@sckcen.be

Copyright © SCK CEN

PLEASE NOTE!
This presentation contains data, information and formats for dedicated use only and may not be communicated, copied, reproduced, distributed or cited without the explicit written permission of SCK CEN.
If this explicit written permission has been obtained, please reference the author, followed by 'by courtesy of SCK CEN'.

Any infringement to this rule is illegal and entitles to claim damages from the infringer, without prejudice to any other right in case of granting a patent or registration in the field of intellectual property.

SCK CEN
Belgian Nuclear Research Centre

Foundation of Public Utility

Registered Office: Avenue Herrmann-Debrouxlaan 40 – BE-1160 BRUSSELS
Operational Office: Boeretang 200 – BE-2400 MOL