DISTEC/DIR/23.0036

KEY ISSUES RELATED TO THE DISPOSAL OF HL VITRIFIED WASTE: FEEDBACK FROM THE CIGEO PROJECT

sumglass

September 27th 2023

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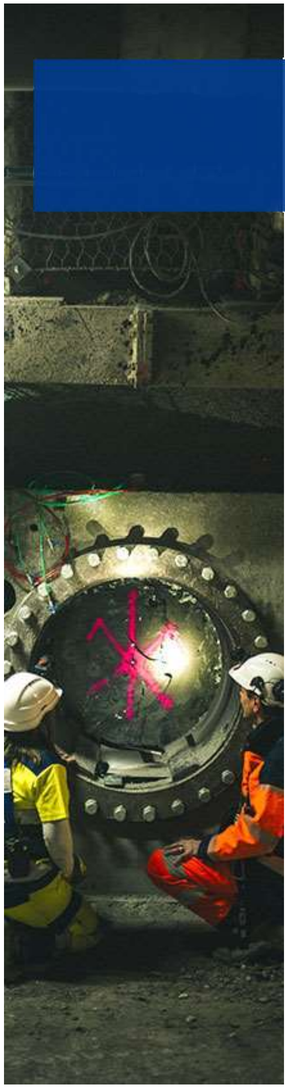
Andra



Cigéo project
Current status and next steps

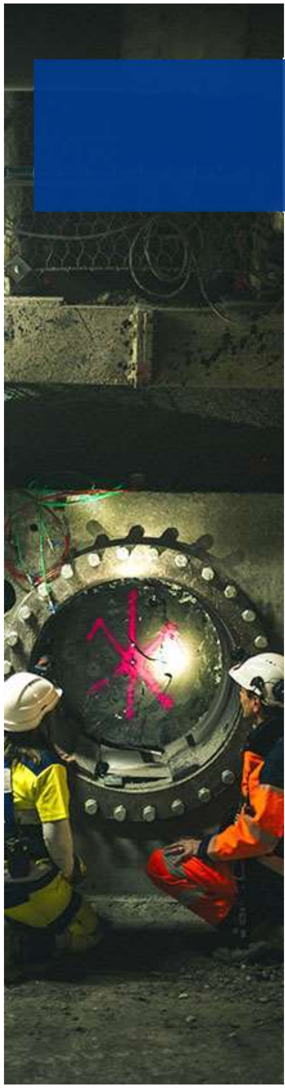
- Submission of the construction license application of Cigéo on January 16th
  - Crucial step marking both a culmination and a new start for the project

- Result of 30 years of progressive development under regular evaluation
- Based on well-defined design principles and a robust safety demonstration
- Over 10,000 pages

  \+ lots of support documents
  - Scientific and technological knowledge base (more than 13,000 pages)

    ⇒ Including vitrified waste behavior (~900 pages)

ANDRA



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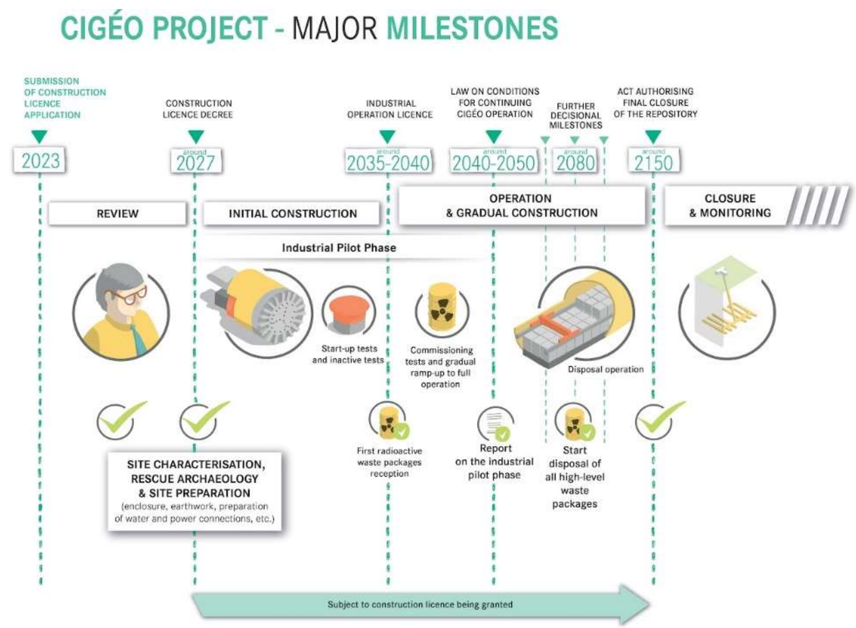

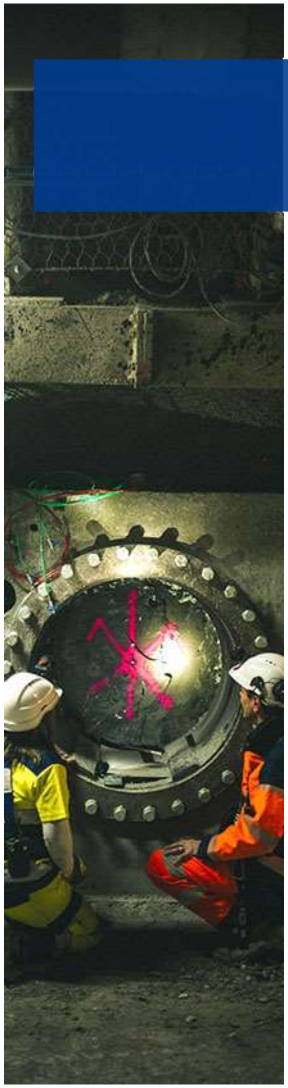

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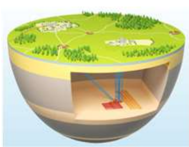
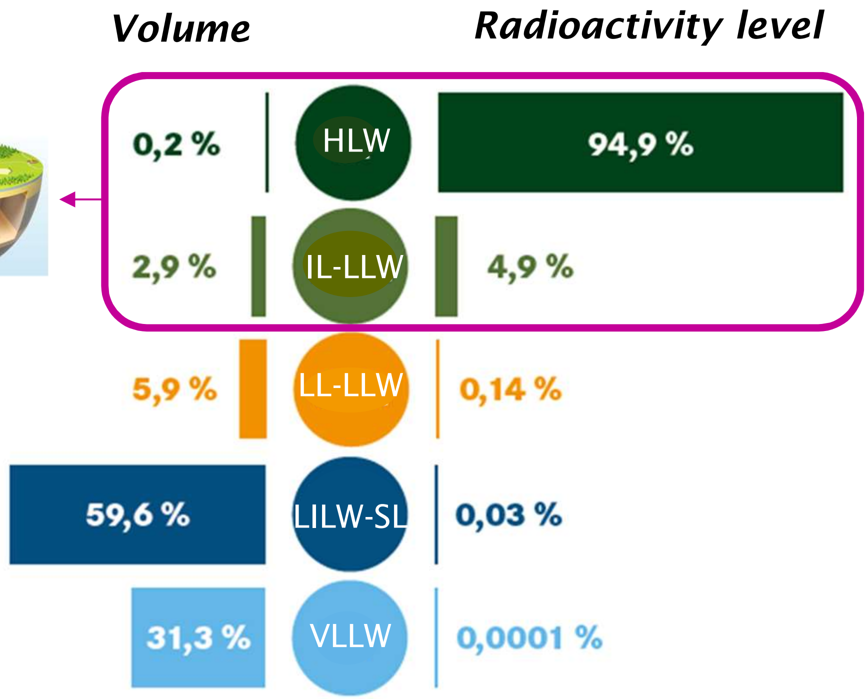
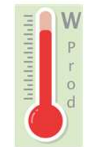
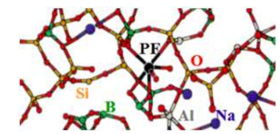
  - A mature project but still tremendous works and numerous steps to become a reality
- Regarding the disposal of HL vitrified waste:
  - What are the lessons learned during the development of Cigéo?
  - Now that Andra has submitted the construction license application and construction of Cigéo could begin in a few years' time, is there still a need for R&D on HL vitrified waste?

Cigéo project
HL vitrified waste inventory









R7T7

UMo

AVM

R7T7	~51,500 ~ 9,300 m^3	1,000 - 2,700	SiO_2 45.1 % B_2O_3 13.9 % FP 13.7 % Na_2O 9.8 %
UMo	~800 ~150 m^3	<50	SiO_2 38.67 % B_2O_3 13.93 % MoO_2 10 % Na_2O 9.39 %
AVM	~3,200 ~ 550 m^3	10 - 400	SiO_2 38.5-46 % B_2O_3 16-19.5 % Na_2O 15.4-18.8 % Al_2O_3 9-12.5 %

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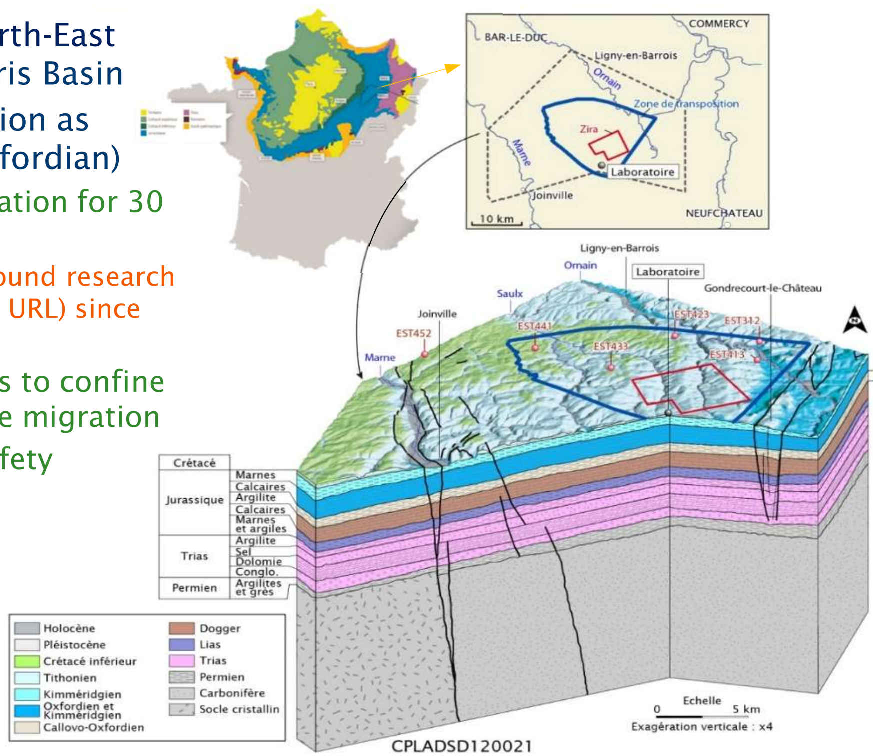
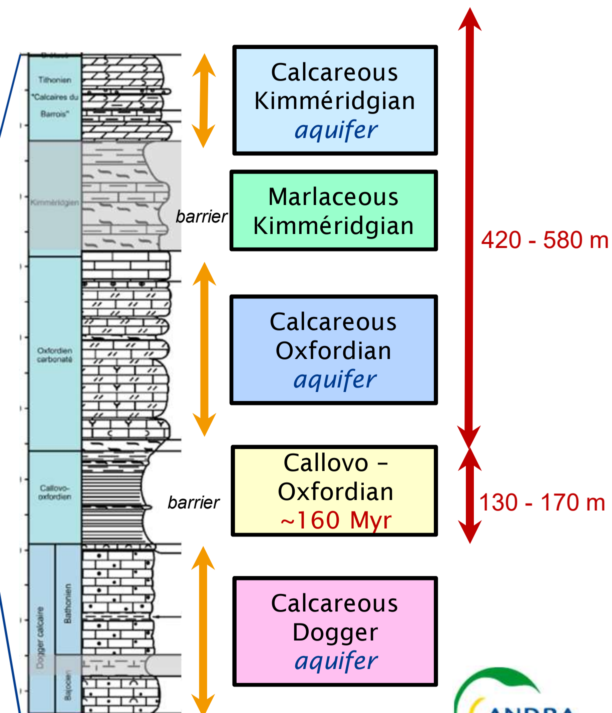
Cigéo project
Site and host rock formation

- Site located in the North-East of France / East of Paris Basin
- Deep clay-rich formation as host rock (Callovo-Oxfordian)
  - Intensive characterization for 30 years
    - Incl. an underground research Laboratory (Bure URL) since 2002
  - Favourable properties to confine and limit radionuclide migration
  - Pillar of long-term safety (with seals of access)





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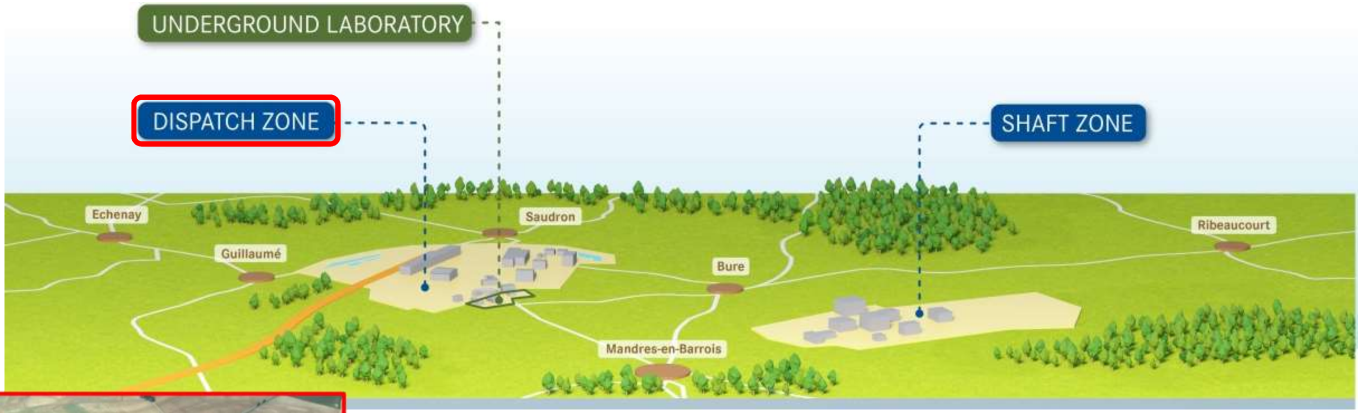
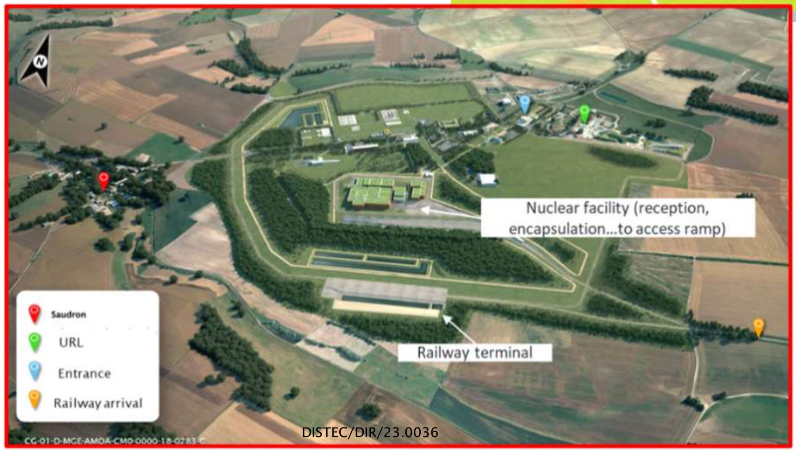
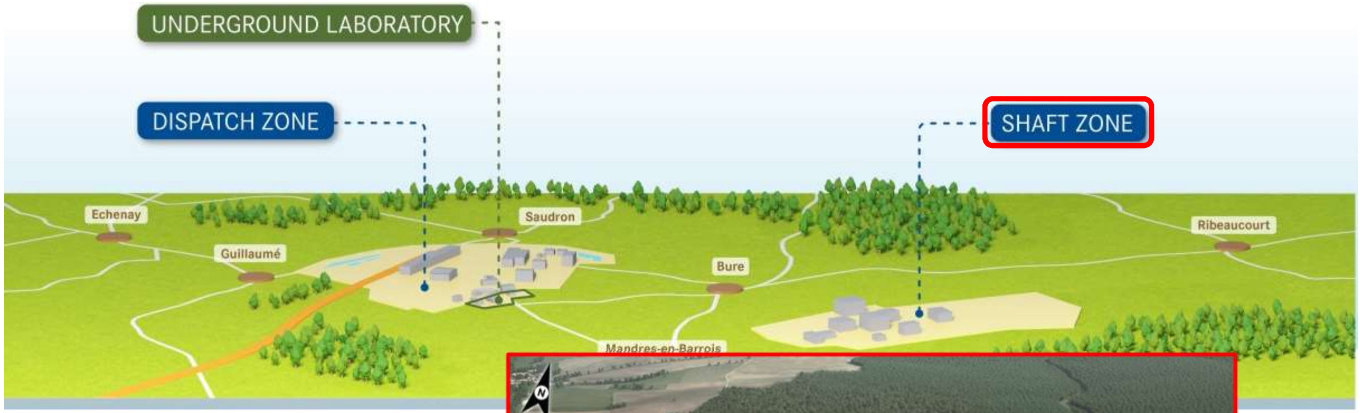
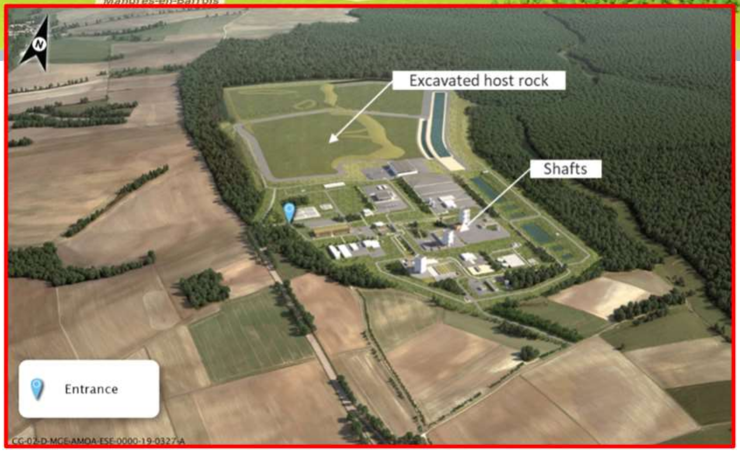
Cigéo project
Surface and underground facilities





Cigéo project
Surface and underground facility





Cigéo project
Surface and underground facility

ILW -LL

HLW

270 Km of galleries

15 km^2 of underground footprint

83000 m^3 of waste

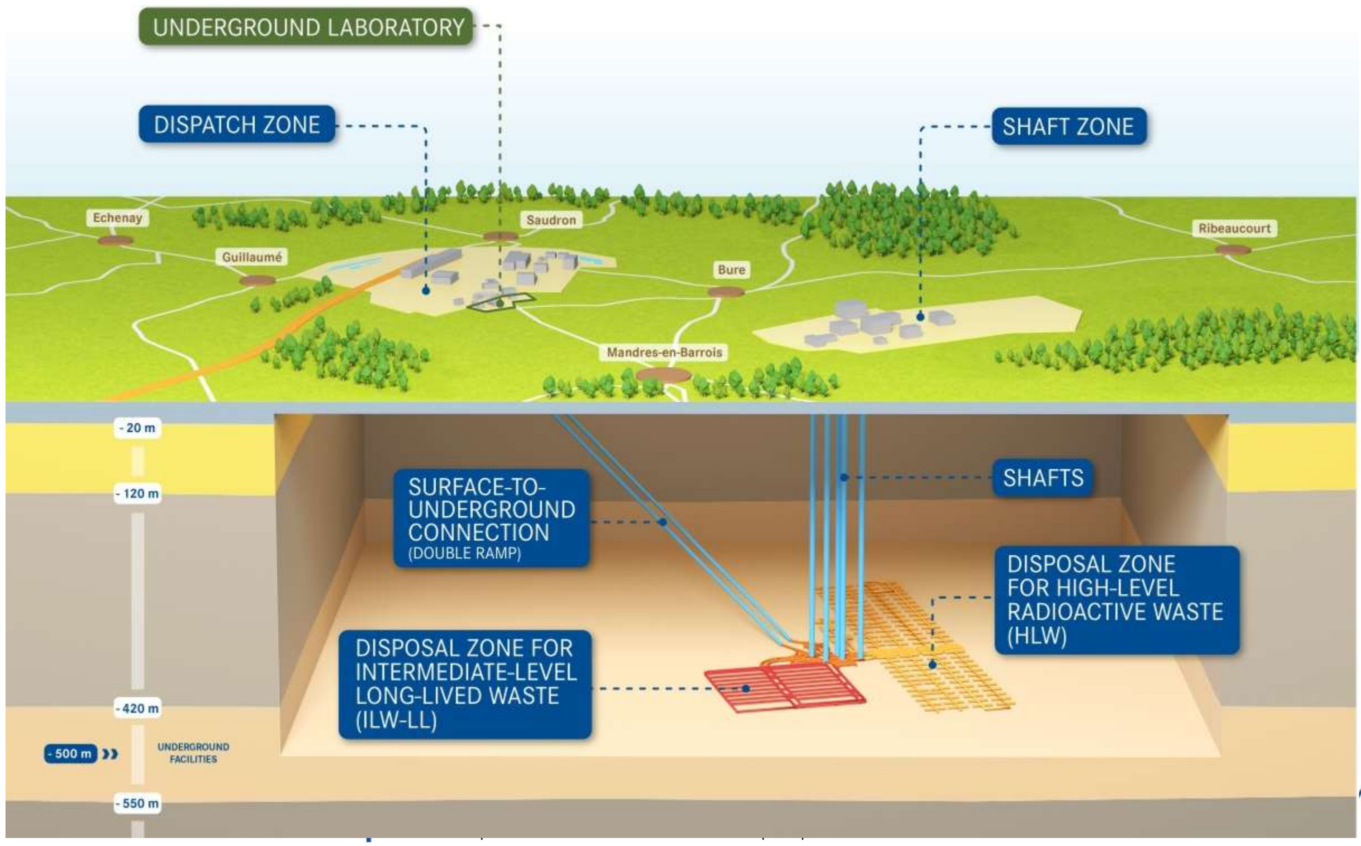
120 Years of operation

25 Bn Euros

10 Mm^3 of excavated materials

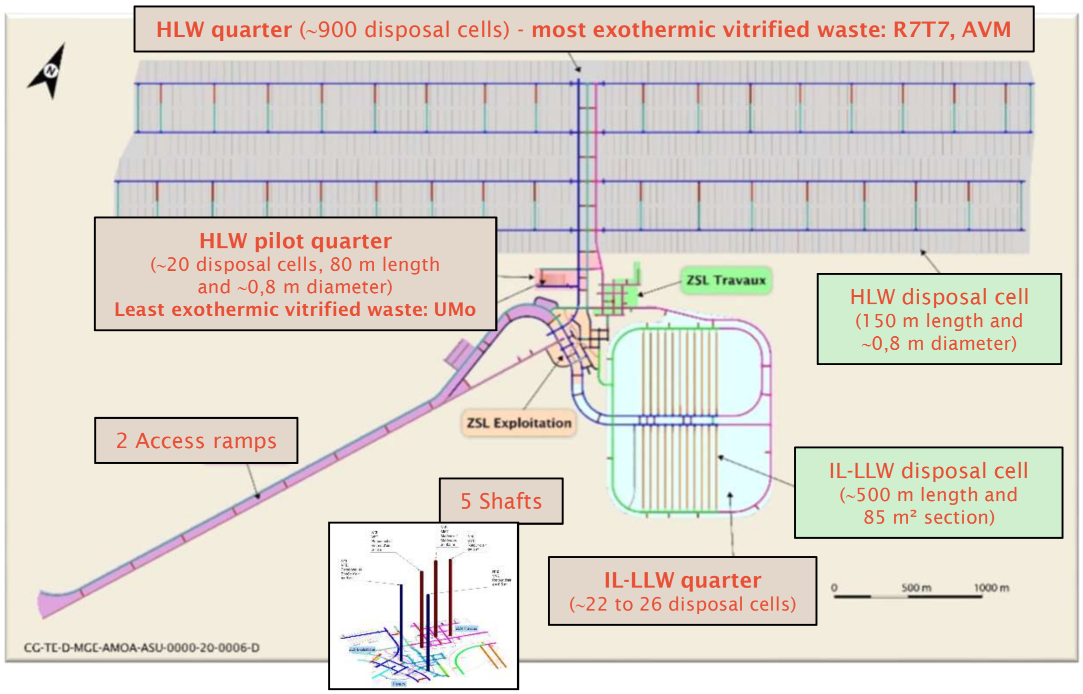
320000 t of steel

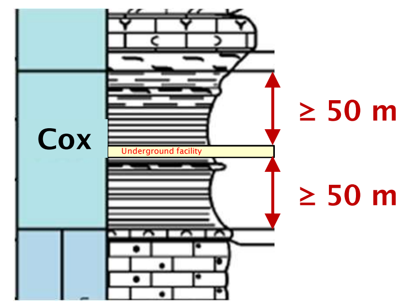
4 Mm^3 of concrete

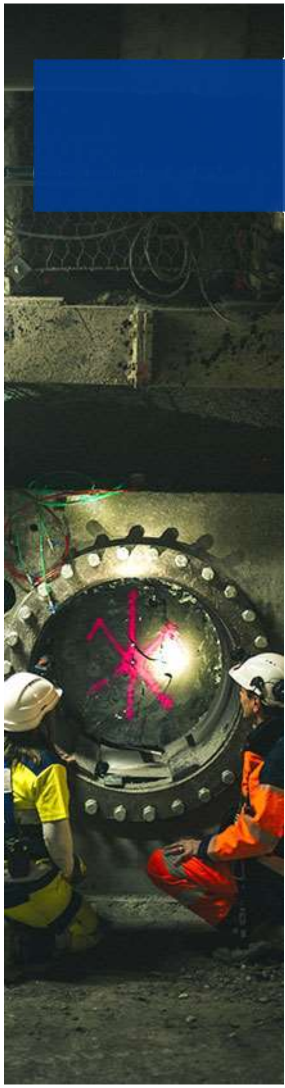


Cigéo project
Underground facility

Designed to be reversible for at least 100 years







Development of the project
The Science – Design – Safety loops

Knowledge acquisition

Design

Understanding of the system

Safety assessment

National and international reviews

New iteration

Research priorities

Feedback to:
- Knowledge
- Uncertainties
- Design

New iteration

Design orientation

About every 4 years

2001, 2005, 2009, (2012), 2016, 2022

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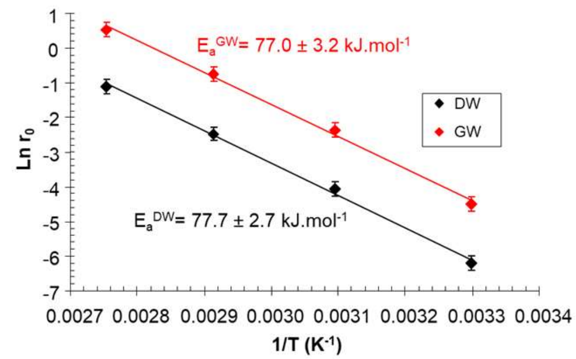
The Science – Design – Safety loops
Influence of design evolution

- At first, the design of the HL vitrified waste disposal cells included a bentonite engineered barrier
- First studies: pure water then clayey water
  - Knowledge based on experiments with FoCa 7 bentonite [1]
    - Same forward rate (2×10^{-3} g/m²/d) with FoCa 7 or in pure water
    - Alteration dropped much faster in pure water

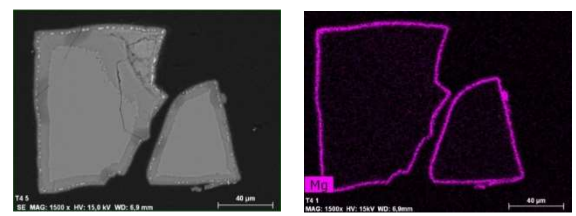
      ⇒ Effect of pH (7.5 in clayey water vs. 8.5 in pure water)

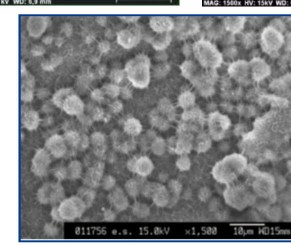


- Abandonment of the bentonite engineered barrier (~2005)
  - Experiments with Callovo-Oxfordian porewater
    - Forward dissolution rate 5 times greater than in pure water [2]

      ⇒ Influence of ionic strength and concentration of alkali metal / alkaline earth cations (mainly Ca^{2+})
    - Rate drop may be delayed (and long-term rate increased) due to precipitation of Mg silicates (leading to a decrease of pH) [3]

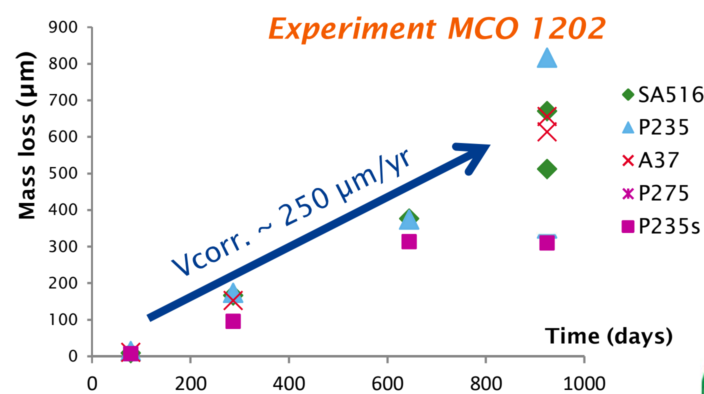
$$H_4SiO_4(aq) + Mg^{2+} + H_2O \rightarrow \text{magnesium silicates} + H_3O^+$$





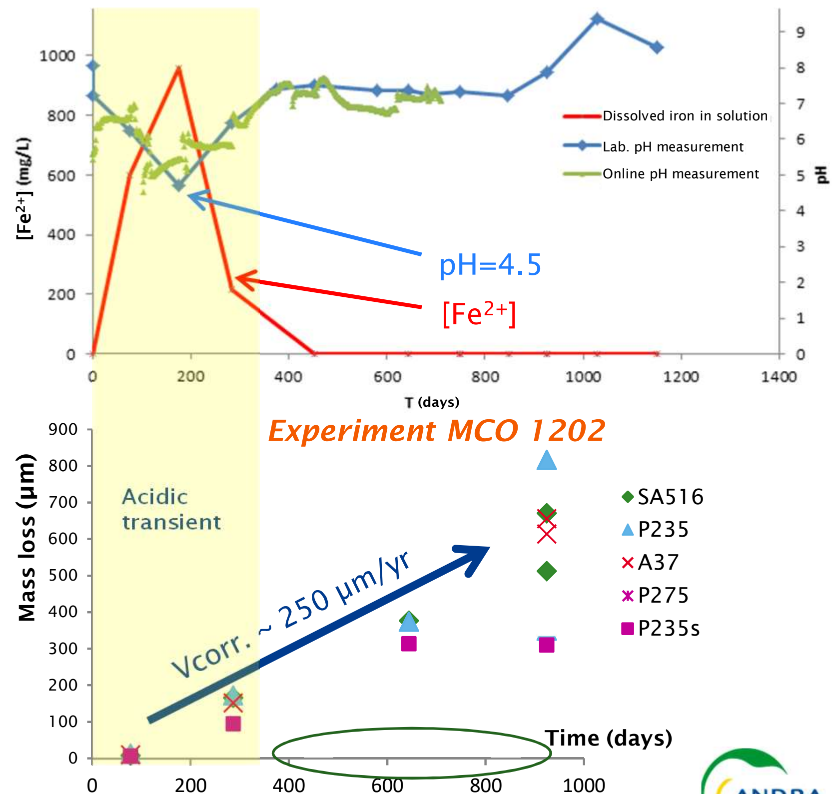
[1] S. Gin *et al.* / Applied geochemistry 16 (2001) 861-881
[2] P. Jollivet *et al.* / Chemical Geology 330-331 (2012) 207-217
[3] P. Jollivet *et al.* / J. Nucl. Mater. 420 (1–3) 508-518 (2012)

The Science – Design – Safety loops
New knowledge → Design evolution → New R&D



The Science – Design – Safety loops
New knowledge → Design evolution → New R&D

- Near-field oxidized claystone creates transiently acidic conditions:
  - Partial dehydration of claystone
    - Increased [Cl-]
  - Pyrite oxidation
    - Formation of sulfuric acid (H_2SO_4)
    - Attack of carbonates ⇒ formation of CO_2
    - CO_2 dissolution ⇒ increased acidity
- Corrosion rates remain high even after returning to neutral conditions



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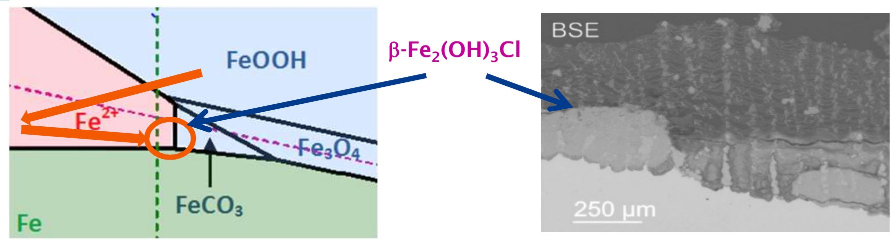
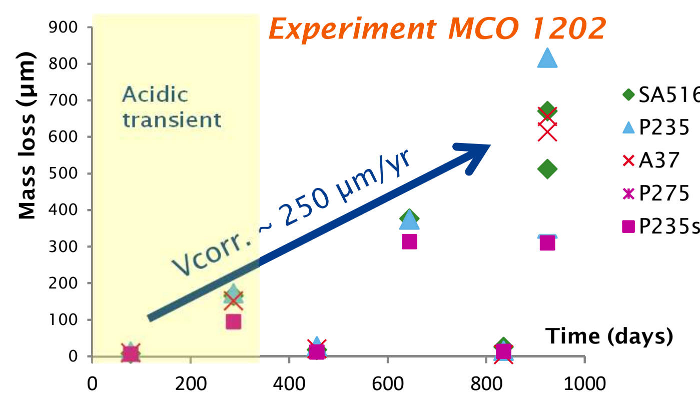
  - "Active" corrosion process under deposits after the acid transient



Interface metal/corrosion products
corrosion in acidic conditions then formation of β-$Fe_2(OH)_3Cl$ under $FeCO_3$
(Vcorr ≈ 250 µm/yr)



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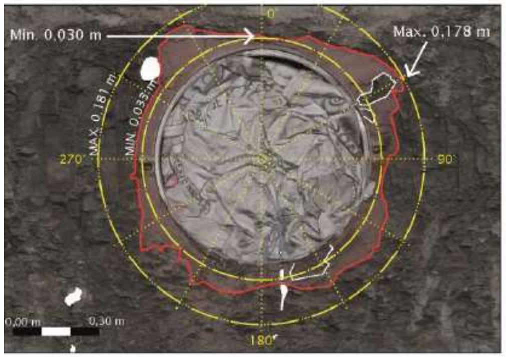
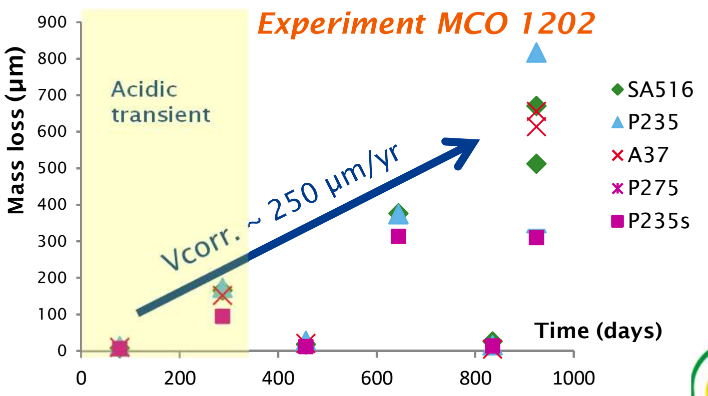
- Corrosion rates remain high even after returning to neutral conditions
  - "Active" corrosion process under deposits after the acid transient
- Two possibilities
  - To carry out R&D to demonstrate the transient nature of high corrosion rate
  - **To modify the design by injecting a cementitious filling grout between the steel sleeve and the host rock (~2014)**
    - Formulate this material and verify the contradictory requirement of corrosion protection and absence of significant effect on glass alteration

    ⇒ **Evolution of the R&D program on vitrified waste**





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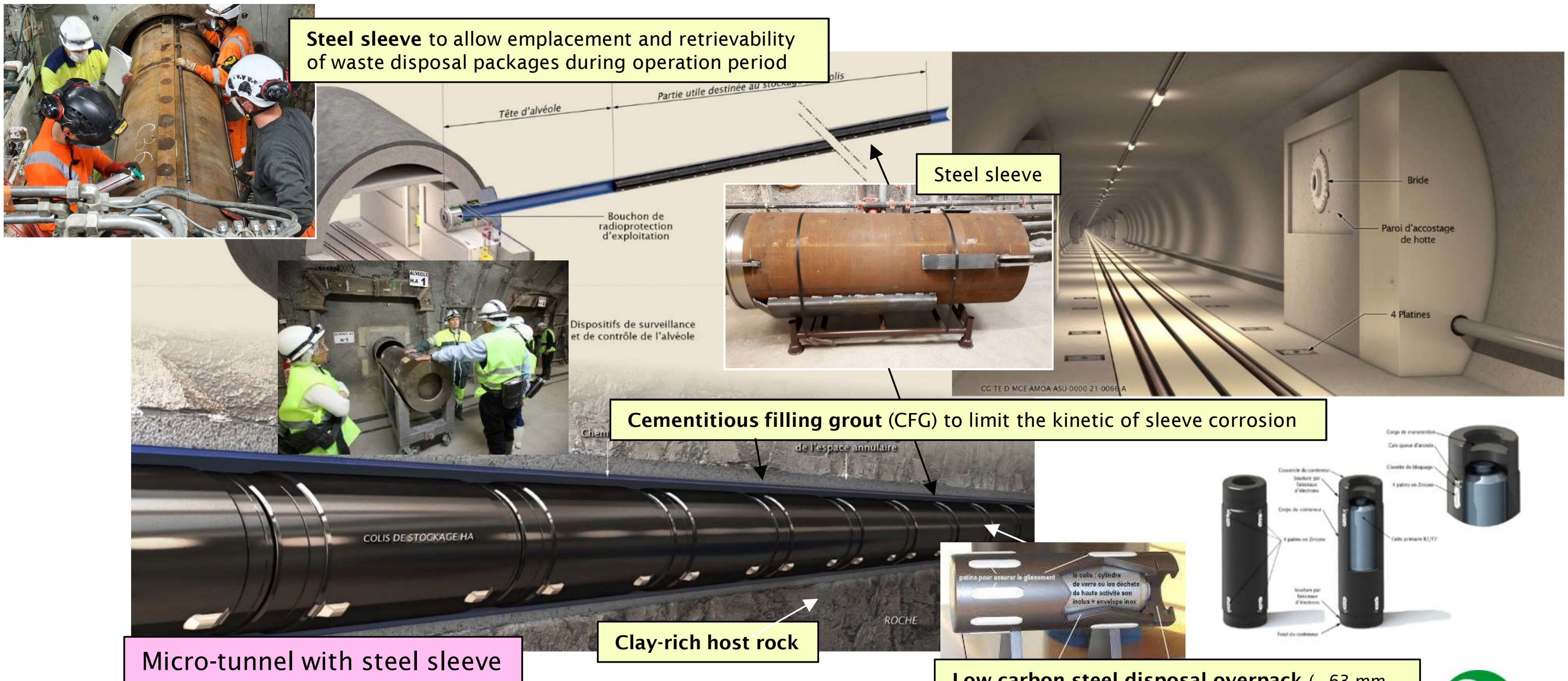
The Science – Design – Safety loops
Evolution of design: HLW disposal cell



Steel sleeve to allow emplacement and retrievability of waste disposal packages during operation period

Steel sleeve

Cementitious filling grout (CFG) to limit the kinetic of sleeve corrosion

Micro-tunnel with steel sleeve

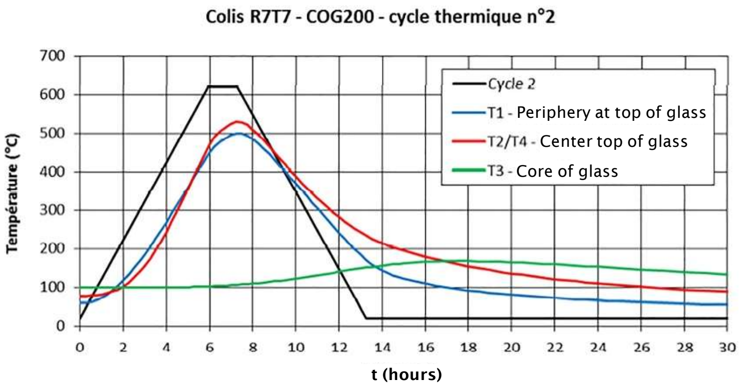
Clay-rich host rock

Low carbon steel disposal overpack (~ 63 mm thickness and ceramic skates) to avoid radionuclide release during thermal phase (several hundred years)

The Science – Design – Safety loops

Evolution following a more precise definition of the project

- Post-weld heat treatment of the overpack lid:
  - Current production methods limit the rise in temperature
    - Treatment of welds in a localized area: choice of induction treatment vs furnace treatment
  - Requirement exceeded in very localized area
    - A few % of the volume on the ends of the glass
- 3 options for dealing with this situation
  - Improve the process to limit glass temperature
    - Modify the thermal stress-relieving cycle
      - Test the limitation of the bearing temperature in the demonstrator workshop
  - Develop a thermal insulator
    - Confirm results obtained with a heat shield made of silica fibers, whose performance has been verified by testing on a representative mock-up
      - This solution has the disadvantages of adding a step to the process and adding a foreign body whose long-term impact remains to be assessed
  - Revise the temperature criterion not to be exceeded for short durations
    - Study the phenomenological risk of glass recrystallization, in relation to the short duration for which the temperature criterion is exceeded



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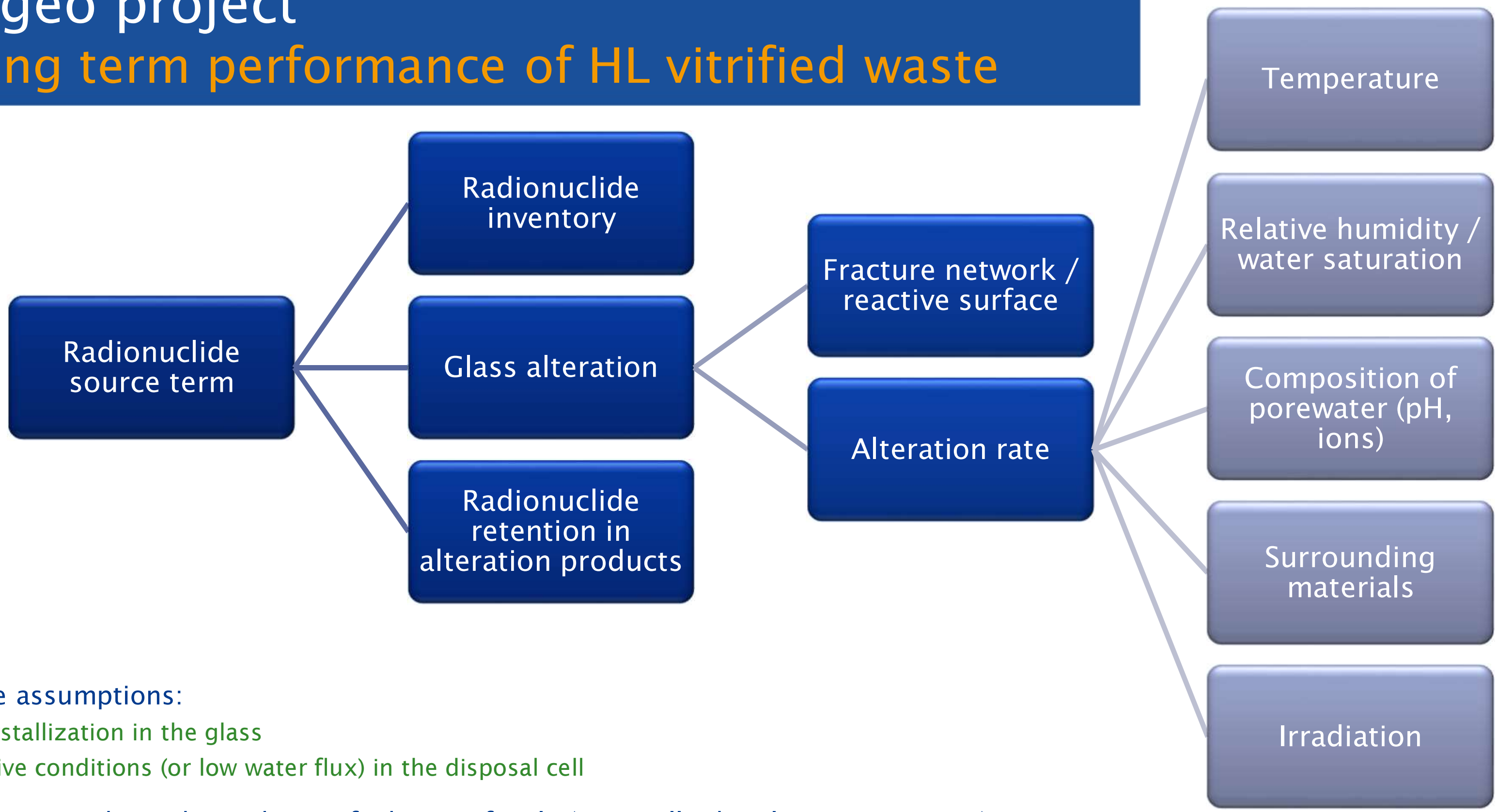
Cigéo project
Long term performance of HL vitrified waste



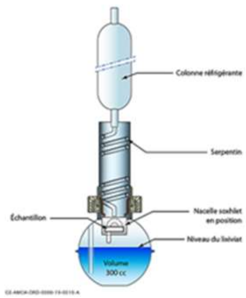
With some assumptions:

- No crystallization in the glass
- Diffusive conditions (or low water flux) in the disposal cell

Most parameters depends on the vitrified waste family (especially the glass composition)

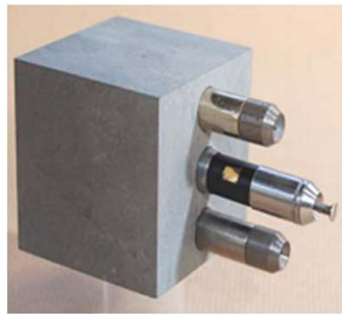
Long-term behavior science [1]

Parametric/mechanistic experiments and mockup



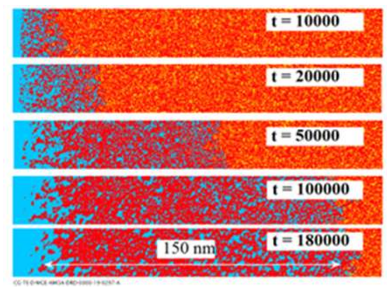
Soxhlet

Glass / corrosion products interactions (CEA)

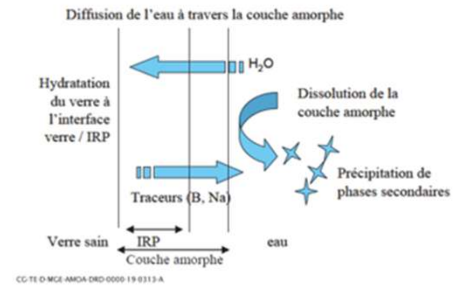


ArCorr (CEA)

Modeling

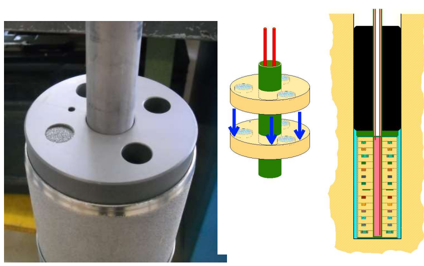


Monte Carlo simulation: evolution of gel (Ledieu, 2004)



GRAAL (CEA)

In-situ experiments

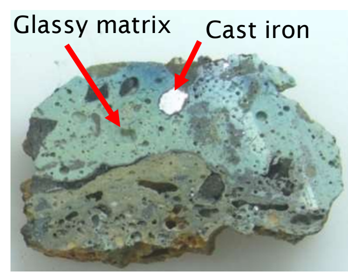


MCO 1231

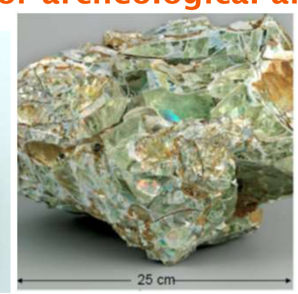
MVE 1202 « long term »

MVE 1201 « rate drop »

Natural or archeological analogs



Glinet 16th century (LAPA)



Embiez Archaeological Glass (CEA)

Basaltic glass

[1] C. Poinssot & S. Gin / Journal of Nuclear Materials 420 (2012) 182-192

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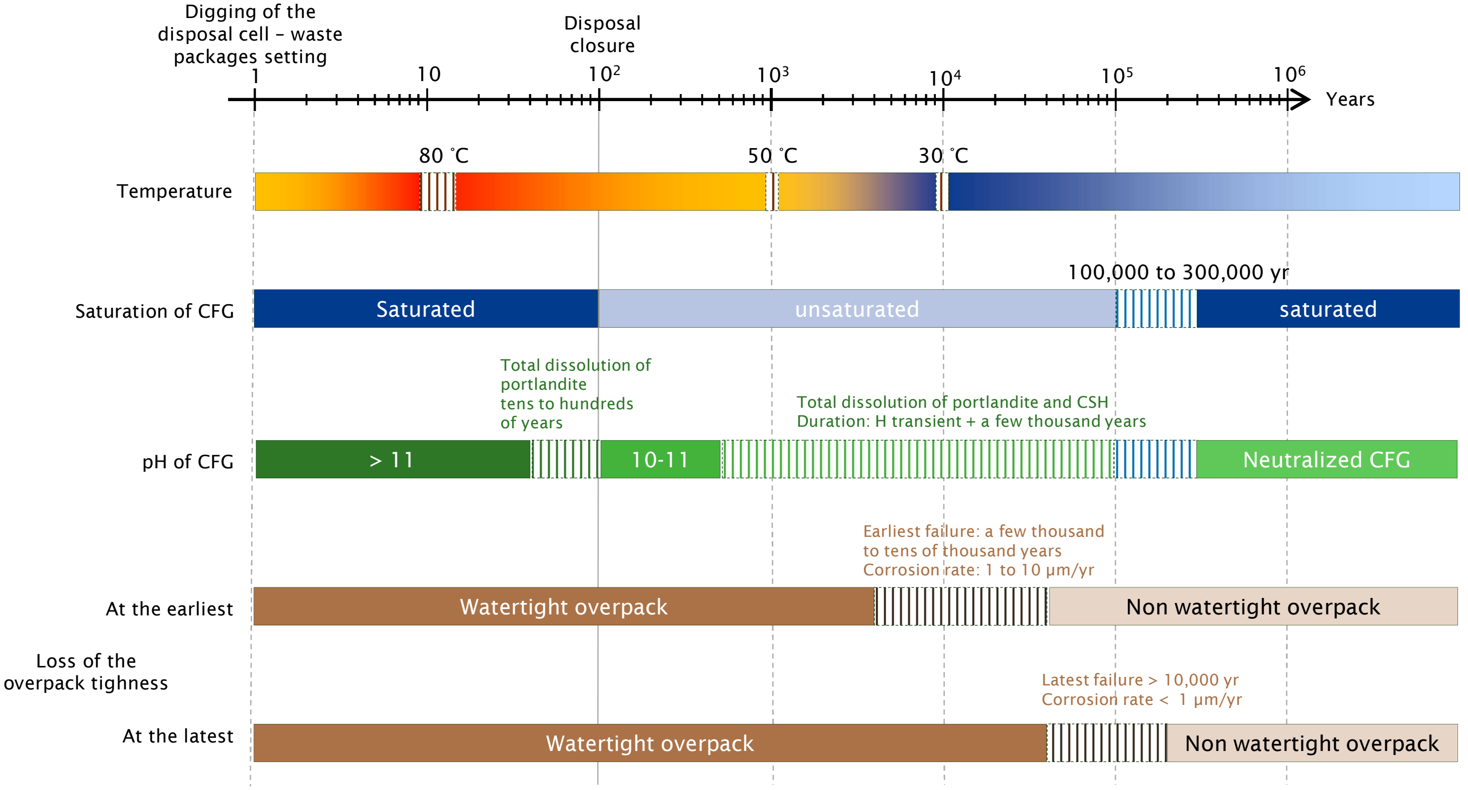
Long-term behavior science
Phenomenological evolution of disposal cells

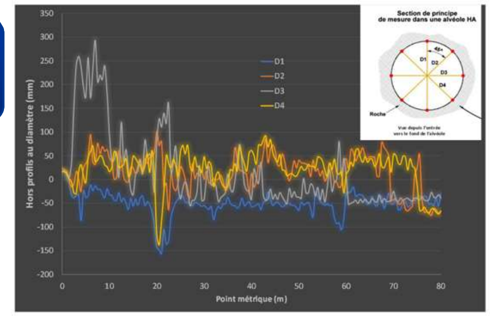


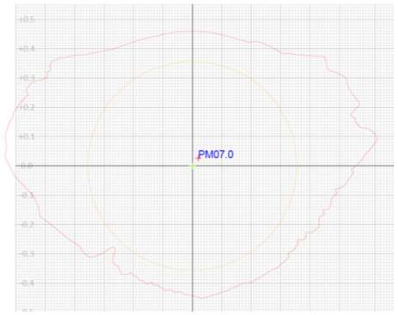
Long-term behavior science
Phenomenological evolution of disposal cells

Disposal cell excavation → Disposal cell geometry

- Volume of oxidized Cox
  Intensity, extension
- Volume of CFG

Off-profile

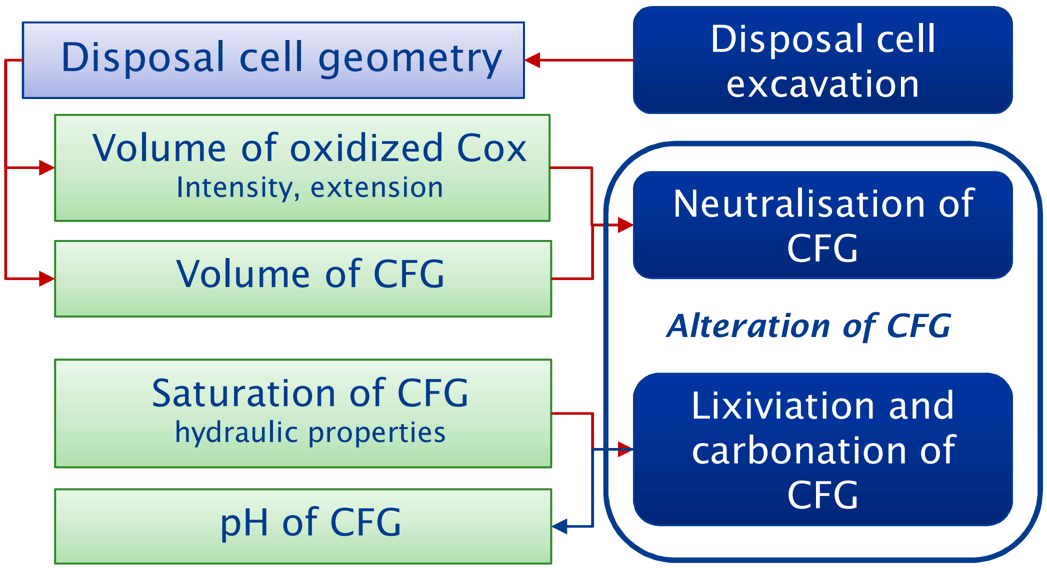




Thickness of cementitious filling grout between 2 and 22 cm (mean value = 8 cm)

Long-term behavior science

Phenomenological evolution of disposal cells



Long-term behavior science
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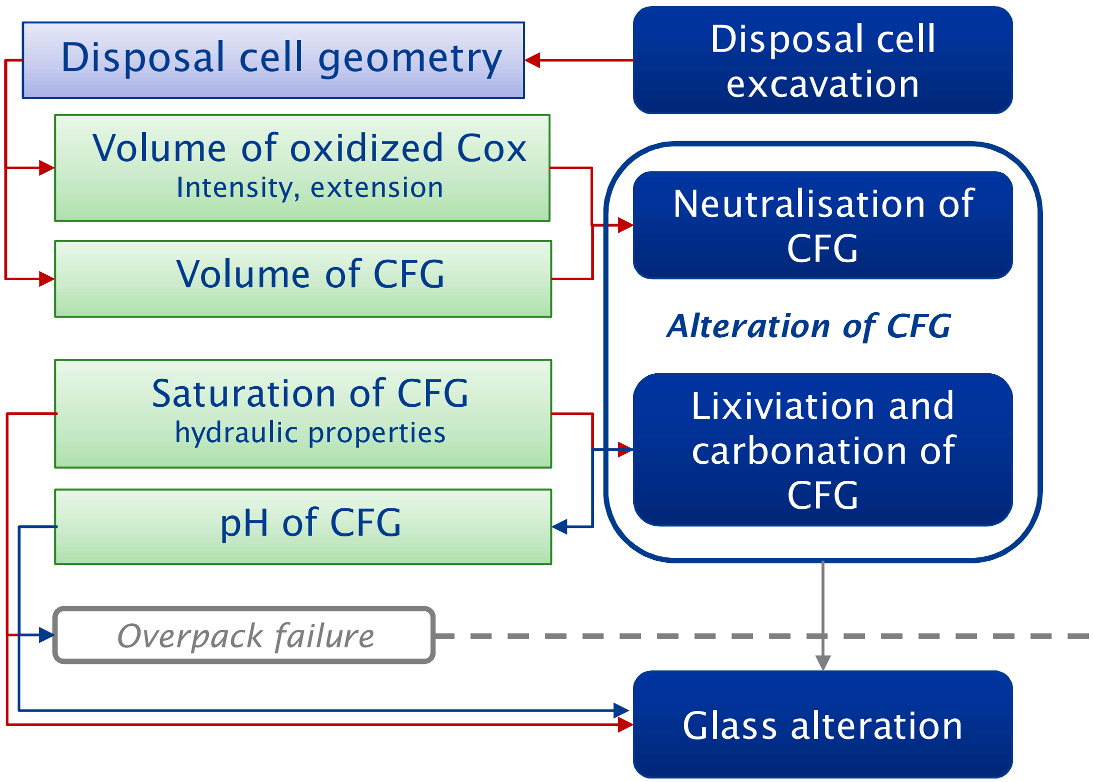
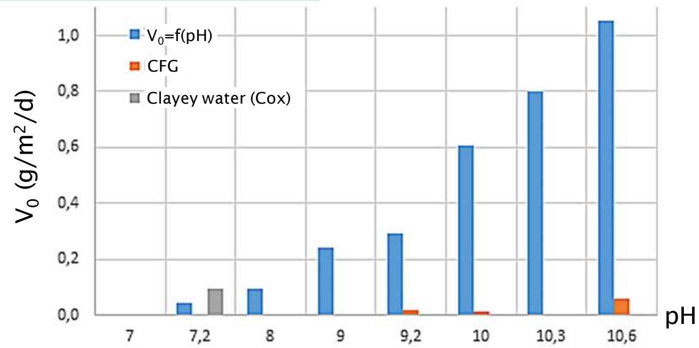
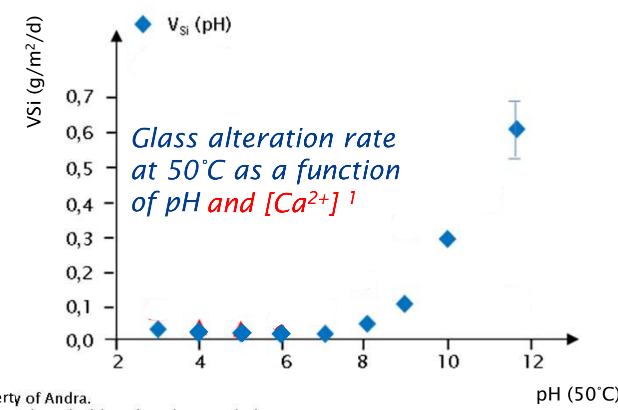




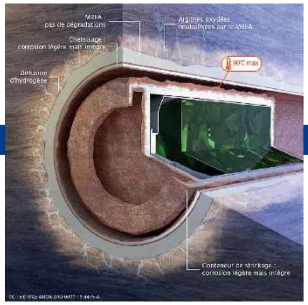
Glass forward dissolution rate at 50°C



Glass alteration rate at 50°C as a function of pH and $[Ca^{2+}]$ [1]

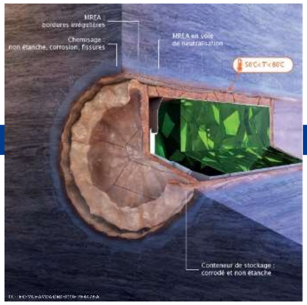
[1] S. Mercado-Depierre *et al.*/ Journal of Nuclear Materials 441 (2013) 402-410

Long-term behavior science
Phenomenological evolution of disposal cells

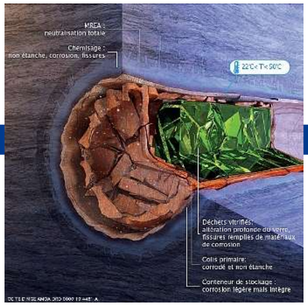


Watertight overpack

After overpack leakage



Unsaturated conditions

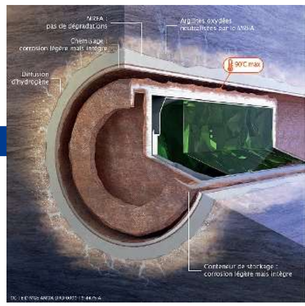


Saturated conditions

Time

R&D based on situations representative of the evolution over time of the HL vitrified waste disposal cells

Long-term behavior science
Phenomenological evolution of disposal cells



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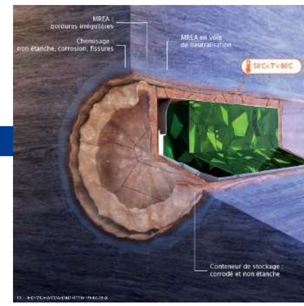

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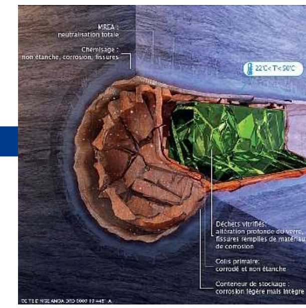
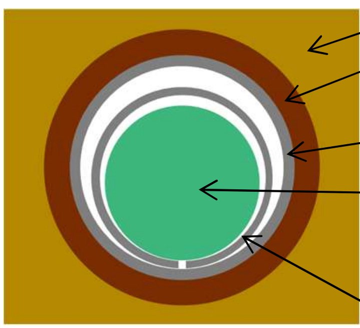


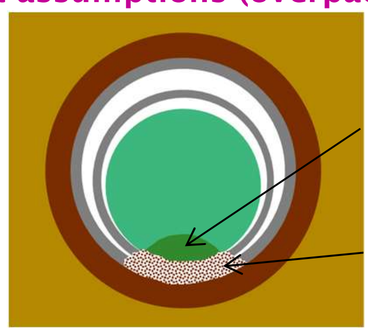
Saturated conditions

Time

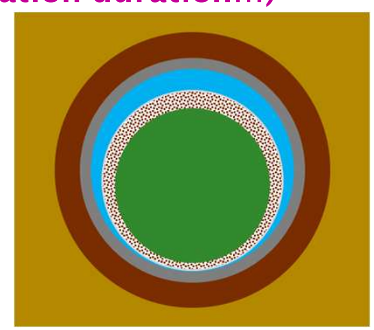
Scenarios corresponding to different assumptions (overpack lifetime, resaturation duration…)



Alteration of the entire glass by water vapor



Alteration of the entire glass by water vapor + local alteration by water

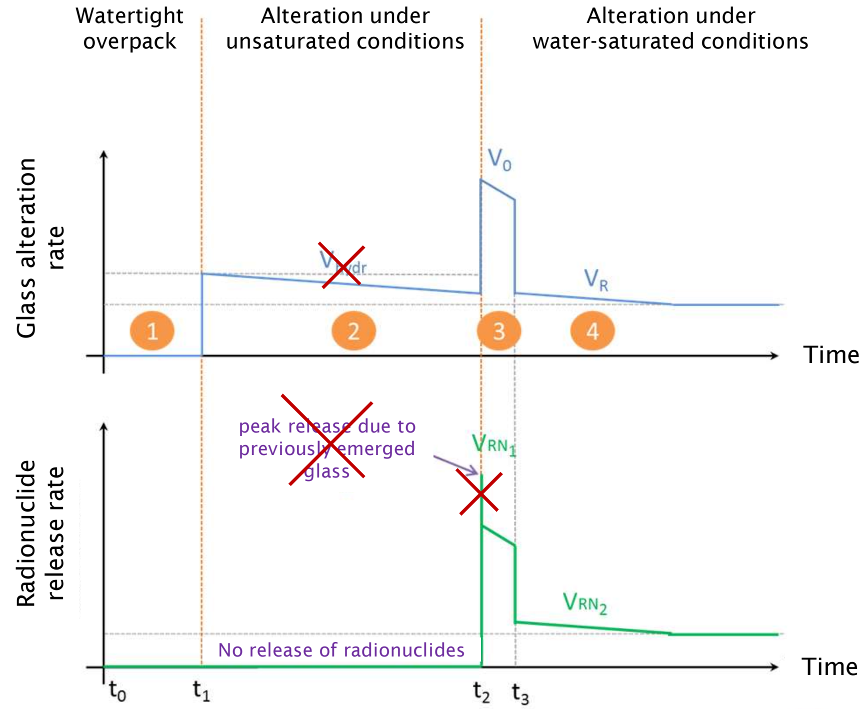


Alteration under water-saturated conditions

Feedback from safety assessment

Normal evolution scenario (saturated conditions)

- Reference situation
  - Best estimate parameters
  - Glass source term: $V_0 \rightarrow V_R$ (for most vitrified waste)
  - Total glass alteration time ~ 230,000 yr
    - Self-irradiation could reduce this time ~20,000 yr

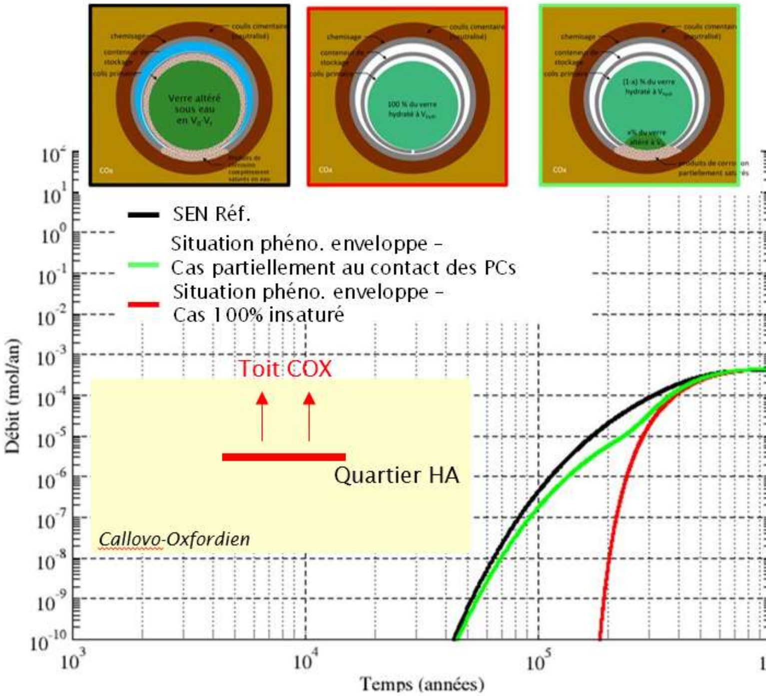


- The model take into account:
  - Mass / surface of metallic matérials
  - Corrosion rate
  - Nature / properties of corrosion products
  - Temperature evolution over time

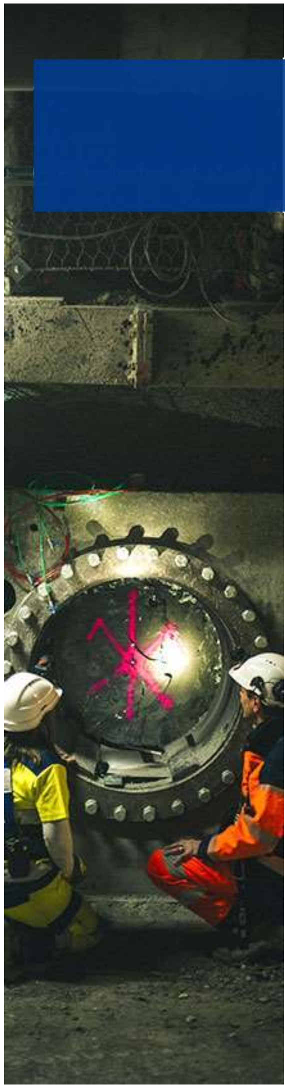
Feedback from safety assessment

Normal evolution scenario (saturated conditions)

- Reference situation
  - Best estimate parameters
  - Glass source term: $V_0 \rightarrow V_R$ (for most vitrified waste)
  - Total glass alteration time ~ 230,000 yr
    - Self-irradiation could reduce this time ~20,000 yr
  - Diffusive transfer in Cox ~ 800,000 yr
  - ⇒ No influence of source term on RN release out of Cox
  - Main RNs: ^{79}Se (VI) (3% HLW), ^{36}Cl and ^{129}I
- Envelope situation
  - Envelope parameters
  - Glass source term: V_0.S ~ 2,000 yr
  - Diffusive transfer in Cox 110,000 (Cl) - 240,000 yr (Se)
  - ⇒ No influence of source term on RN release out of Cox
  - Main RNs: Se (-II/0) (80% HLW), ^{129}I and ^{36}Cl



Release of ^{129}I at the top of Cox



Which R&D for the future?

CMC Liner

Ceramic overpack

R&D on vitrified waste is linked to

- The maturity of project development
- The "Science/ design / safety " loops, which continue even after the disposal has been commissioned
  - New input data, new knowledge, etc.

Feedback from safety assessments

- The cornerstone of the safety is the host-rock with the glass matrix playing a minor role

But safety assessment of Cigéo is based not only on dose calculations, but also on an understanding of how the system works

- Need to develop tools that provide a more realistic representation of the evolution of vitrified waste, and in particular taking into account finer couplings with the evolution of the environment

So there is still R&D to be done, but it is focused on topics that can have a significant influence on glass durability or on the dose to the outlet

- A finer understanding of the environmental evolution
- Glass alteration with water vapor: long term rate, influence of fractures, influence of irradiation
- Glass alteration in water-saturated conditions:
  - influence of self-irradiation
  - Interactions between glass and its environment (carbon steel, cementitious materials…)
- To a lesser extent, inventory and speciation of Se in the glass

THANK YOU FOR YOUR ATTENTION