femto-st SCIENCES & TECHNOLOGIES

Radioactive Waste Management & Risks

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introduction

professionnal activities

- Associate Professor & Researcher at **Institut FEMTO-ST, Dpt Energie** (since 2007)
- Manager_Magnetocaloric Research Pole_Energy Dpt, FEMTO-ST Institute (since 2015)
- Energy systems & Energy Transition team
- Expert @ Citizen Climate Convention, France (2020)
- Expert @ **Information & Assessment Mission _ Deep Geothermal Energy_Eurometropole Strasbourg** (2021)
- Hearing @ **Parliamentary Information Mission _ Closure of the Fessenheim NPP** (2021)
- Hearing @ **OPECST** (French parliamentary office for the evaluation of scientific and technical choices)_**risks of irradiation-induced thermal aging of nuclear steels**
- Scientific contributor to **SFEC** – **French Strategy for Energy and Climate** (2022-23)

main research

- ***Fluid mechanics and conjugate heat transfer*** (1980-2023)
- ***Turbulence, transition to turbulence*** (1990-2023)
- ***Magnetocaloric effet & devices*** *for cooling and heat pumping* (2008-2023)
- ***Solar thermal energy & design of solar heating systems for buildings*** (1989-2023)
- ***Geothermal systems*** (1980-2023)
- ***Nuclear energy, nuclear safety & risks, ageing and fracture mechanics in nuclear steels*** (1977 – 2023)
- ***Assessment, modelling & optimization of complex energy systems*** (1983-2023)
- ***Modelling of energy policies & energy transitions towards sustainable energy systems*** (2010-2023)

nuclear materials in the nuclear energy industry

radioactive material and waste from French nuclear power industry

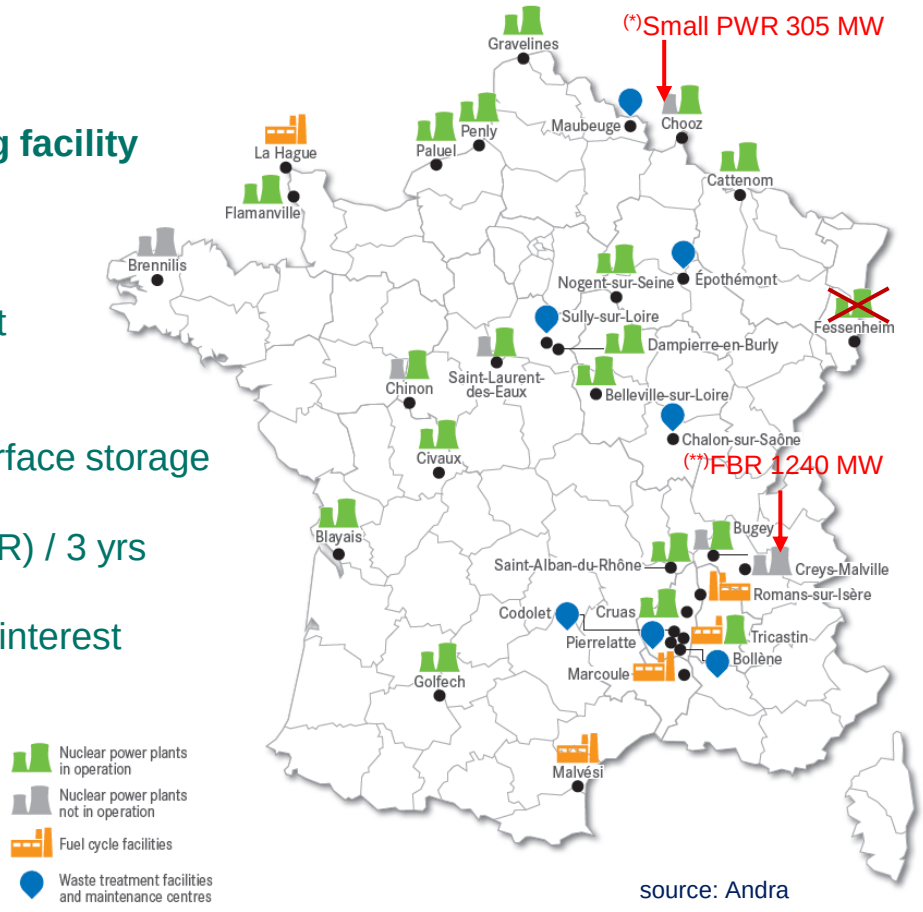
❑ historical milestones

- 1945 – creation of the French Atomic Energy Commission (CEA)
- 1950-69 – CEA's research reactors, EDF's GCG(*) reactors, **nuclear fuel reprocessing facility** (La Hague, Marcoule), immersion of radioactive waste (RW) in oceans
- 1974-99 – commissionning of 58 PWR (900 MW – 1400 MW) + 1 FBR(**)
- 1979 – creation of the ANDRA (**National Radioactive Waste Agency**) from CEA
- 1981 – creation of the « Castaing » Commission for the radioactive waste management
- 1991 – « Bataille » law_research on radioactive waste management
  → ANDRA = *public industrial and commercial company*
  → 3 axes for LLRW: *separation/transmutation *deep-geological storage *long-term surface storage
- 2000 – construction of the Underground Research Laboratory
- 2006 – law for **National Radioactive Materials & Waste Management Plan** (PNGMDR) / 3 yrs
- 2019-21 - consultation on the preparation of the 5th edition of the PNGMDR
- 2023 - request for authorization to create **Cigéo**, public inquiry for declaration of public interest

❑ nuclear power plants and installations in France

- in operation: 56 PWR (1977-)
- closed/decommissionned: 2 PWR (Fessenheim, 2020)
- dismantling: 1 HWR, 3 GCGR, 1 PWR, 1 FBR
- nuclear fuel reprocessing facility

PWR – Pressurized Water Reactor
HWR – Heavy Water Reactor
GCGR – Gas Cooled Graphite Reactor
FBR – Fast Breeder Reactor
LLRW – Long Life Radioactive Waste
Cigéo - Industrial Geological Storage Center



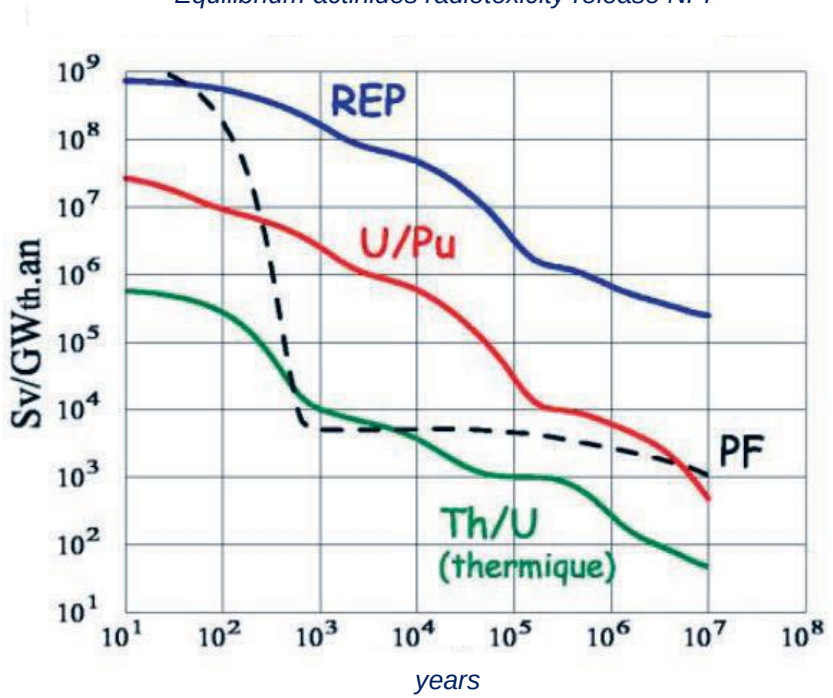
source: Andra

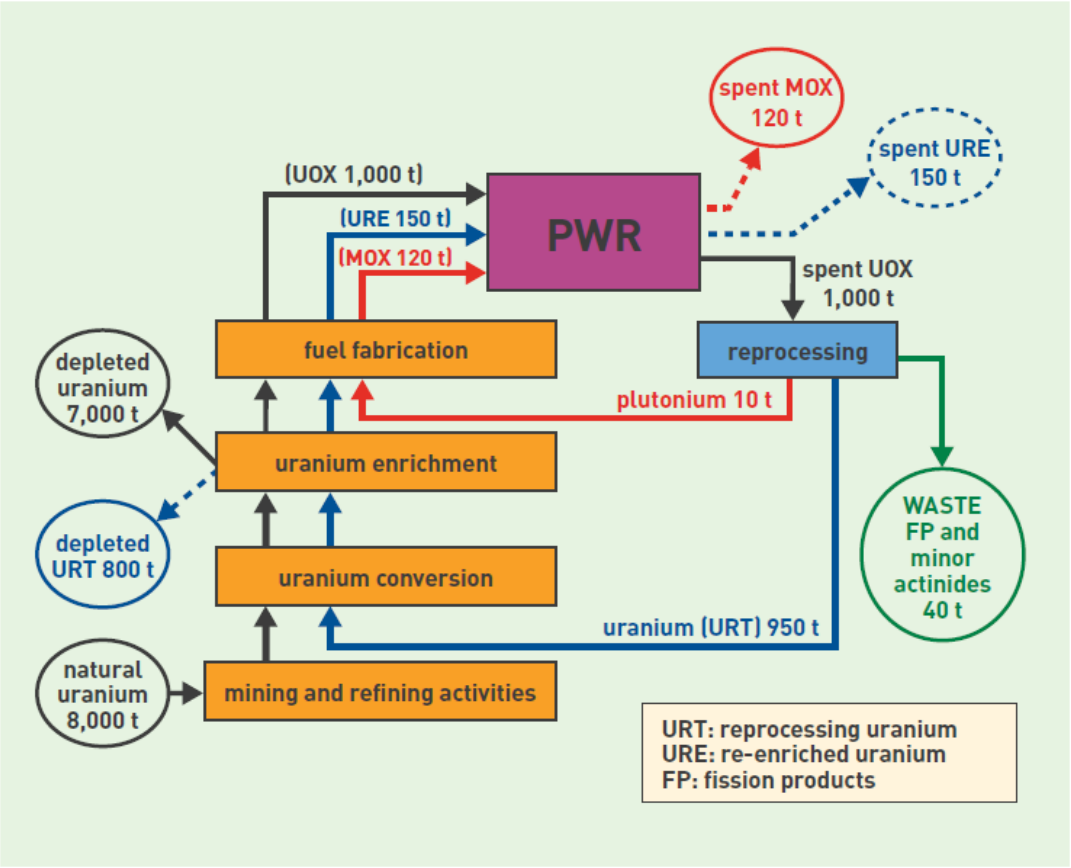
inventory of nuclear materials in France

National Radioactive Materials & Waste Management

- **production of radioactive materials and waste by the nuclear power sector in France**

Equilibrium actinides radiotoxicity release NPP





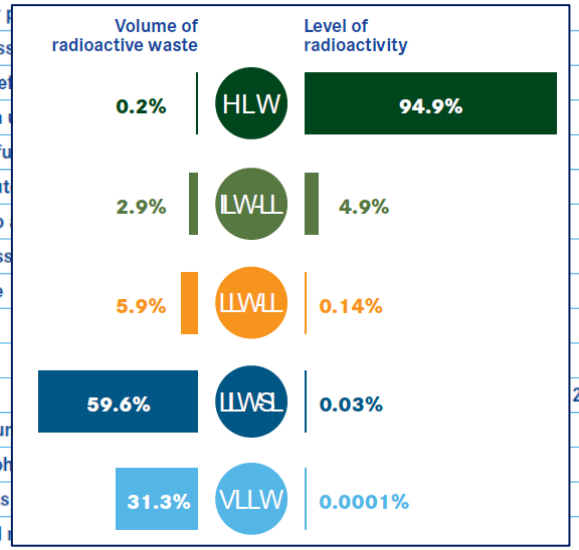
sources: CNRS, CEA

inventory of nuclear materials in France

National Radioactive Materials & Waste Management

N°	Material category (in ton)	As of end 2021	2021/2020 trend	Foreign share
1	ENU fuels before use	733	+121	
2	ENU fuels in use in nuclear power plants	3970	-100	
3	Spent ENU fuels pending reprocessing	11200	+100	0.3%
4	ERU fuels before use	-	-	
5	ERU fuels in use in nuclear power p	-	-1	
6	Spent ERU fuels pending reprocess	630	+3	
7	Mixed uranium-plutonium fuels bet	11	-16	
8	Mixed uranium-plutonium fuels in	215	-108	
9	Spent mixed uranium-plutonium fu	2390	+160	
10	Non-irradiated mixed uranium-plut	337	+22	
11	Non-irradiated uranium fuel scrap	-	-	
12	Spent FBR fuels pending reprocess	125	+2	
13	Research reactor fuels before use	0.04	-	
14	Fuel in use in research reactors	1	-	
15	Other civil spent fuel	61	+1	2%
16	Spent fuel for defence purposes	202 tonnes	+4 tonnes	
17	Non-irradiated separated plutoniur	65	+5	24%
18	Mined natural uranium, in all its ph	37800	-2000	
19	Enriched natural uranium, in all its	3290	-100	
20	Enriched uranium from spent fuel	-	-	
21	Uranium from spent fuel reprocessing, in all its physical-chemical forms[2]	34200	+100	8%
22	Depleted uranium, in all its physical-chemical forms	324000	-	
23	Thorium, in the form of nitrates and hydroxides	8510	-50	
24	Materials in suspension (by-products of rare earth ore processing)	5	-	
25	Other materials[3]	70	-	

ENU – Enriched Natural Uranium
ERU – Enriched Reprocessed Uranium
FBR – Fast Breeder Reactor



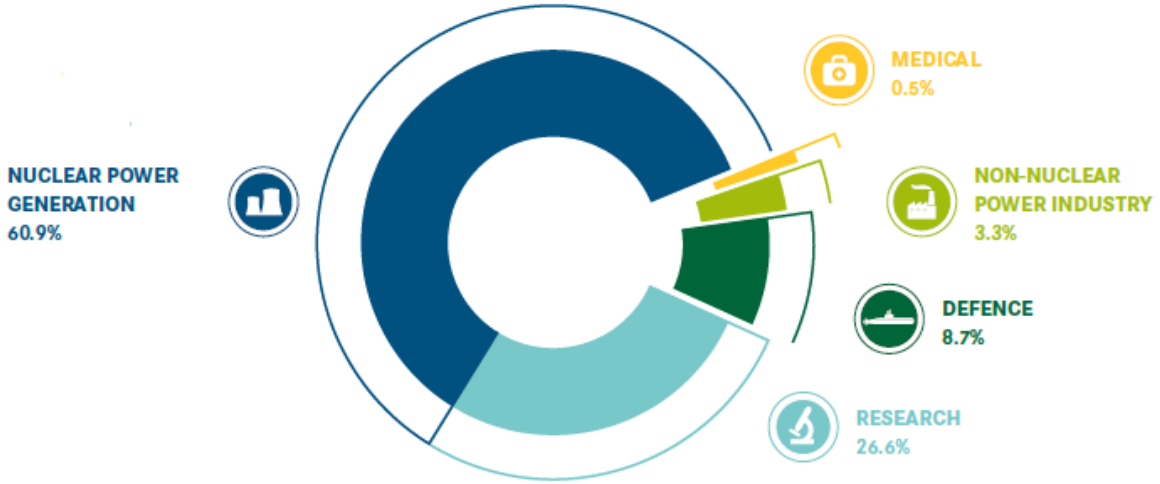
Activity** \ Radioactive half-life	Very short-lived (VSL) (half-life < 100 days)	Mainly short-lived (SL) (half-life ≤ 31 years)	Mainly long-lived (LL) (half-life > 31 years)
Very low level waste (VLLW) < 100 Bq/g	Management through radioactive decay	TFA: Surface disposal (Industrial facility for grouping, storage, and disposal)	
Low-level waste (LLW) between a few hundred Bq/g and one million Bq/g		FMA-VC: Surface disposal facility (Aube and Manche disposal facilities)	FA-VL: Near-surface disposal facility under study
Intermediate-level waste (ILW) in the range of one million to one billion Bq/g			MA-VL: Deep geological disposal facility under development (Cigeo project)
High-level waste (HLW) on the order of several billion Bq/g	Not applicable	HA: Deep geological disposal facility under development (Cigeo project)	

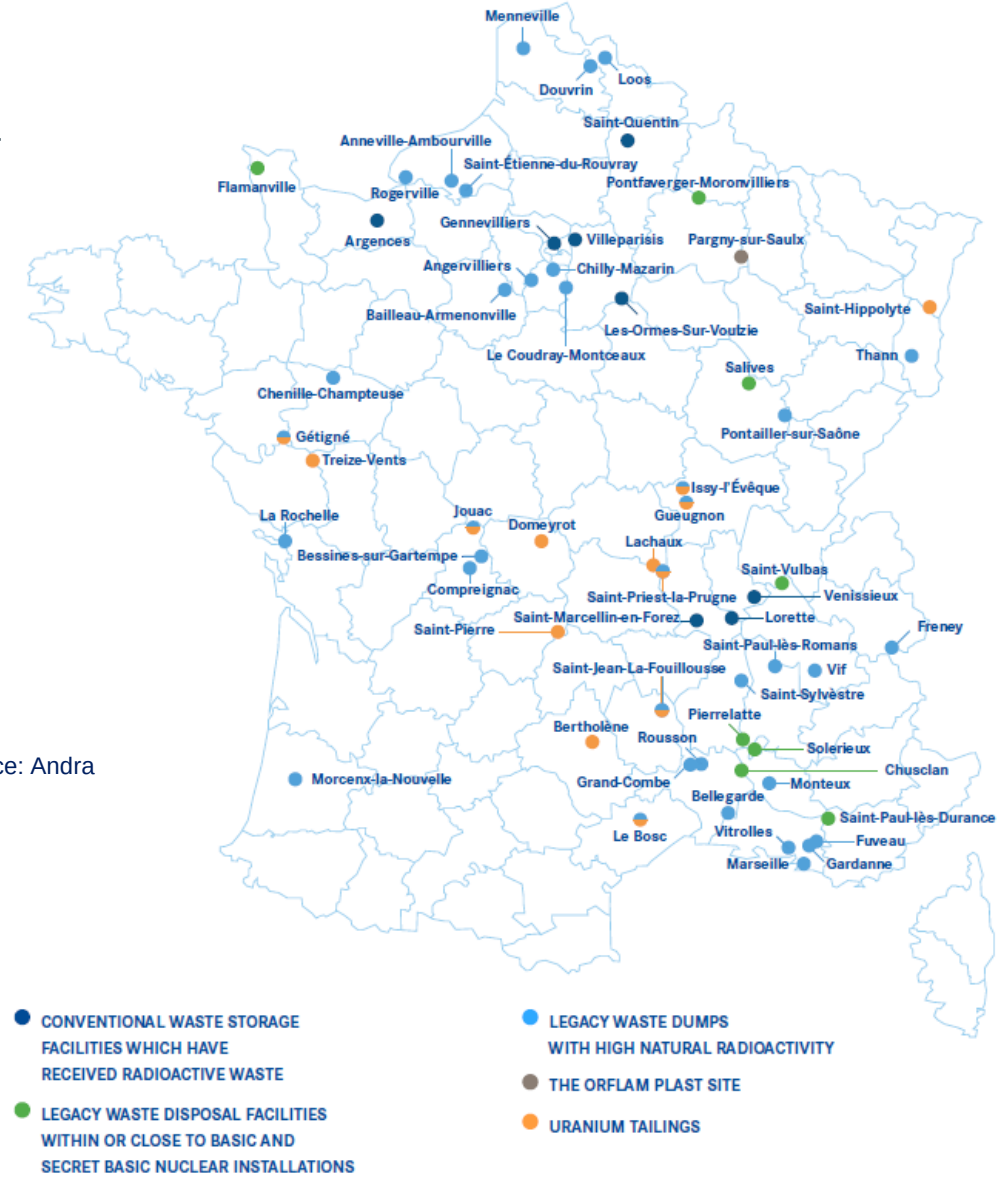
Category (primary package in m³)	Total	At producer/ holder sites	Disposed of at Andra facilities	Existing disposal capacity
HLW	4320	4320	-	-
ILW-LL	39500	39500	-	-
LLW-LL	103000	103000	-	-
LILW-SL	981000	91000	890000	1,530,000
VLLW	633,000	203,000	430,000	650,000
DSF	304	304	-	-
Total	~ 1,760,000 m³	~ 441,000	~ 1,320,000	2,180,000
		25%	75%	

source: Andra

inventory of nuclear materials in France

National Radioactive Materials & Waste Management





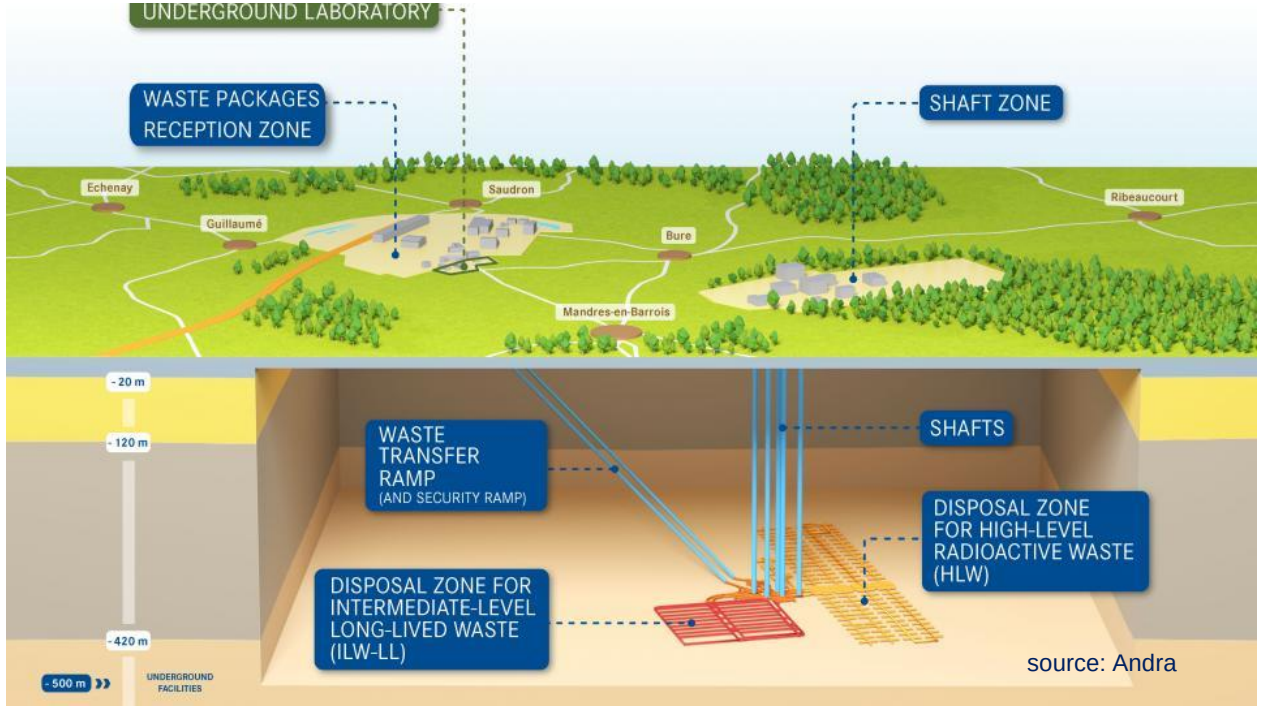
source: Andra

energy data France 2021-22:
nuclear electricity ≡ 65-70% electricity consumption, 16% of total final energy consumption

management of nuclear waste – facilities & projects

radioactive waste repositories in France

- **Very-Low Level & Low-Level Waste**
  - surface disposal facilities
    - VLLW: CIRES (Aube dept, Champagne region)
    - LIL-SLW: CSA (Aube dept, Champagne region)
    - LIL-LLW: CSM (Manche dept, Normandie region)
      → graphite: ^{14}C (5730 yrs, β), ^{36}Cl (300000 yrs, β)
- **High-Level & Intermediate-Level Long-Lived Waste** (1)
  - CIGEO project (in Bure, Aube department, Champagne region)
    - 29 km²
    - ~ 350 km of concrete galleries in clayrock (argillite)
    - HL packages (vitrified) → lateral disposal cells (100 m, 70 cmØ)
    - IL-LL packages (asphalt, concrete) → lateral tunnels (500 m, 10 mØ)
    - robotic filling
    - 500 m underground
    - 4 vertical shafts + 1 waste transfer ramp
    - permanent ventilation 600 m^3/s (hydrogen, radioactivity, gases)
    - 3 wagons/day HL-IL/LL waste during decades
    - reversibility during 100 yrs



(1) www.andra.fr
http://cpdp.debatpublic.fr/cpdp-cigeo/_script/ntsp-document-file_downloadda21.pdf?document_id=157&document_file_id=165
http://cpdp.debatpublic.fr/cpdp-cigeo/_script/ntsp-document-file_download8fba.pdf?document_id=158&document_file_id=166

management of nuclear waste in France – risk assessment

risks, uncertainties on PNGMDR & Cigéo project

- **Risks, other issues**
  - **thermal instability** of burried packages in cells (25 MW)
  - degassing of dissolved **alkanes generated** in clayrocks(2)
  - uncontrolled **fires** (asphalt packages) → Stocamine (chemical products in salt layer,2002), WIPP (radioactive waste in salt mine, 2014)(3)
  - **hydrogen** explosions (water radiolysis, metal oxidation) (3)
  - **outer flooding** of galleries (storms, rivers though shafts and ramp)
  - **inner flooding** of galleries (Gallo-Oxfordian aquifer above, Dogger aquifer below) (4)
  - **migration of radioactive products in aquifers** (4)
  - **radioactivity release** (6000 GBq/yr ^{85}Kr, 300 GBq/yr ^{3}H, 300 GBq/yr ^{14}C, natural radioactivity x 2)(4)
  - **GHG** emission (11 $MtCO_{2eq}$ / construction & operation?)
  - **seisms**, ground movements (faults), **geothermal energy compromised**(4)
  - ventilation **failure**, **power** consumption
  - terrorist **attacks**
- **uncertainties**
  - overall **cost** (35 G€ ?)
  - thermal behavior of **asphalt packages**
  - **waterproofing** of galleries, tunnels, cells
  - long-term **mechanical behavior of argillite layer**
  - **irreversibility** in case of accident, blocking, overheating, hydrogen concentration excess, etc. → moral responsibility towards future generations

(2) Lerouge et al., *Dissolved CO_2 and alkane gas in clay formations*, Proc Earth Planet Sci 13 (2015) 88-91
(3) Schroeder V., Holtappels K., *Explosion Characteristics of Hydrogen-Air and Hydrogen-Oxygen Mixtures at Elevated Pressures*, International Conference on Hydrogen Safety, Pisa, Italy, Paper No. 120001 (2005)
(4) French Environmental Authority report, 2022,

management of nuclear waste in France – alternative solutions

existing and future radioactive waste

- **High-Intermediate-Level Long-Lived Waste**
  - dry, long-term storage in subsurface disposal facilities (protected horizontal reinforced concrete shed)
    - improvement of conditioning (vitrification, canister)
    - permanent monitoring & control (corrosion, heating, safety)
- **Low-Level Short-Lived Waste**
  - dry, long-term storage in subsurface disposal facilities (protected horizontal reinforced concrete shed)
    - improvement of conditioning (vitrification, canister)
    - permanent monitoring & control (corrosion, heating, safety)
    - possible storage of LL-SL radioactive devices inside nuclear reactor buildings after decommissionning
    - possible volume reduction by melting (reuse? risk of radioactive dissemination in commercial steels? electric consumption?)

future management of nuclear materials

- **spent nuclear fuels**
  - continuation of reprocessing irradiated nuclear fuels
    - continous production of HIL-LL waste
    - research on **multirecycling MOX** (mix of U-Pu oxydes)
    - Gen IV subcritical reactors to use Pu & depleted U, actinides
  - no continuation of reprocessing irradiated nuclear fuels[5]
    - dry, long-term storage in subsurface disposal facilities (Nuhoms system Orano[6], Holtec[7])
      → improved earthquake & flooding resistance and safety
  - research on **transmutation of minor actinides** (Np, Am, Cm) → *needs research on separation of MA*
    - no solution yet for transmutation of fission products ($^{137}Cs/^{135}Cs$)

[5] https://skb.com
https://www.posiva.fi/en/

[6] https://www.orano.group/usa/en/our-portfolio-expertise/used-fuel-management/used-fuel-storage/nuhoms-eos-canister
[7] https://holtecinternational.com/products-and-services/nuclear-fuel-and-waste-management/

thank you for attention

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