Waste management and advanced reactors

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- Impact of LFR Design on radioactive waste & spent fuel

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- Radioactivity sources in LFR

- Radioactivity of lead coolant and cover gas and RW generated by coolant and cover gas purification

- ^{210}Po management in LFR

- Management of the Pb-contaminated items

- Management of radioactive waste from ALFRED operation and decommissioning

- Management of ALFRED spent fuel

Radioactive waste generated from current NPPs

❑ The electricity generated from nuclear reactors results in **small amount of waste** that has to be safely managed and for which the **nuclear sector takes full responsibility**

❑ Comprehensive and robust **waste management plans** represent **pre-requisite for licensing** as part of the safety case for construction or operation license

❑ Mature technology for waste processing (excepting few challenging waste) and facilities for storage and disposal exists
  - LLW- near-surface disposal
  - ILW - shallow deep disposal
  - Spent fuel:
    - reprocessing and HLW disposal
    - direct geological disposal

➢ *on average, the waste from a reactor supplying **a person's electricity needs for a year** would be about the **size of a brick**. Only **5 grams** of this is **HLW** (the weight of a sheet of paper)*

Total volume of nuclear waste
- HLW
- ILW
- LLW
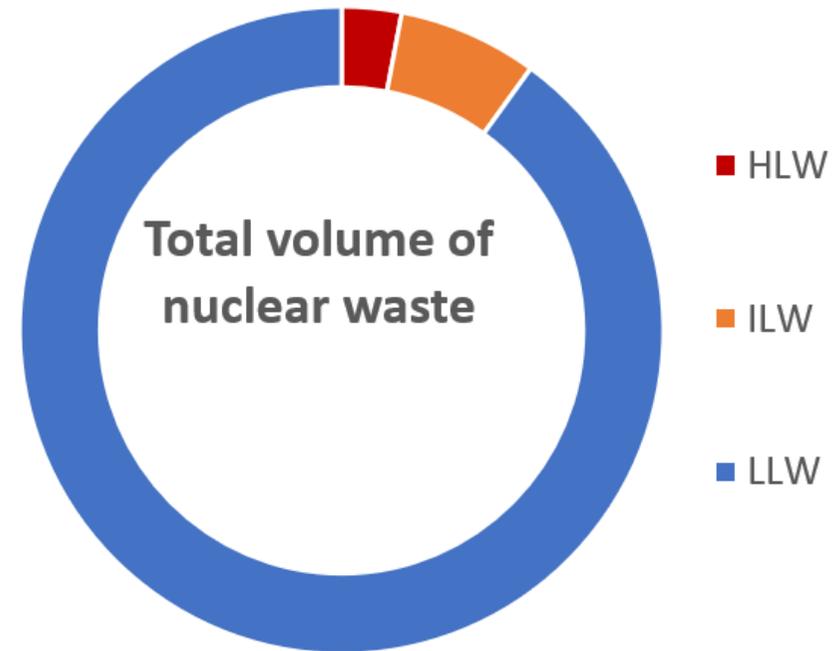
HLW – (SF or waste from reprocessing) containing **95% of radioactivity** in the nuclear waste	3%
ILW - used filters, steel components from within the reactor and some effluents from SF reprocessing, containing **4% of radioactivity** in the nuclear waste	7%
LLW, lightly-contaminated items from routine operation, containing only **1% of radioactivity** in the nuclear waste	90%

https://world-nuclear.org/nuclear-essentials/what-is-nuclear-waste-and-what-do-we-do-with-it

Impact of LFR Design on RW & Spent Fuel

The impact of LFRs on waste is a "**double-edged sword**." While they are **significantly more efficient in reducing the long-term burden of SF**, they introduce **new challenges for RW and SF management**

- ➢ LFRs operate with a **fast neutron spectrum**, which allows them to **fission transuranic elements** (like Pu, Am, Cm and Np) that thermal reactors typically leave behind as waste
  - ○ LFRs can use Mixed Oxide (MOX) or Mixed Nitride (MNUP) fuels, **effectively "burning" the plutonium and minor actinides recovered from thermal reactors SF** (CANDU or PWR)

- ➢ LFRs can be designed to allow **long-lived fission products transmutation** (converting them into shorter-lived RNs) ⇒ **reduced radiotoxicity**
  - ○ the period during which the waste remains **hazardous drops from 300,000 years to roughly 300 - 1,000 years**

- ➢ Higher fuel burnup is achieved in LFRs ⇒ the **amount of SF** generated per GWh of electricity can **be significantly lower** than in thermal reactors

- ➢ LFRs allow **more efficient use of resources**
  - ○ by using in LFRs reprocessed fuel, the energy extracted from the same amount of initial uranium can be multiplied by a factor of 60 to 100

- ➢ Unlike water, **lead is a heavy metal that creates specific waste streams** during operation and decommissioning

- ➢ **LFR spent fuel** is technically **more demanding to manage** than thermal reactor fuel

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Each advanced reactor technology exhibits unique characteristics that influence the volume & composition of the RW and SF with impact on the management technologies and disposal routes

❑ **Coolant: Lead**

➢ RNs from **activation of Pb and Pb impurities**;

➢ **Chemical hazard linked to Pb** (hazardous chemical)

❑ **Structural materials:**

- **316LN:** austenitic SS as primary structural material

- **15-15Ti:** advanced austenitic SS for fuel cladding

➢**RNs from the activation of material components and corrosion products**

❑ **Nuclear fuel – MOX** with higher Pu content (~21.7-27.8% Pu) than MOX used in thermal reactors

❑ **Rapid neutron flux**

➢ **SF with higher temperature & radioactivity** due to the higher content of Pu and FPs compared to thermal reactor's SF

Lead used as coolant creates unique waste streams due to volatile activation products: **210Po** and **203Hg**
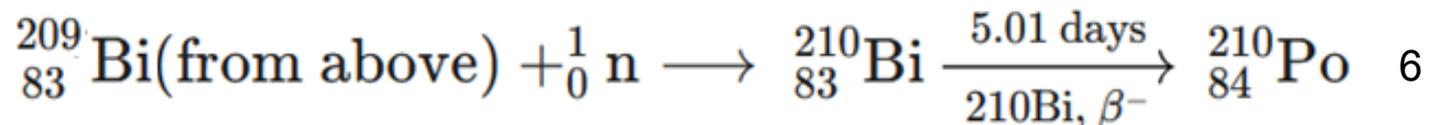
> ➤ need for sophisticated gas and coolant purification

210Po (α emitter, $T_{1/2}$ = 138.4 days) poses a unique radiological hazard due to its **high radiotoxicity**, **volatility**, and **mobility** within the primary system $\Rightarrow$ it can **enter the cover gas** as an aerosol $\Rightarrow$ a major **inhalation risk** during maintenance or waste processing

210Po generation routes in LFR coolant:

- **209Bi (impurity) neutron capture:** $^{209}_{83}\text{Bi} + ^{1}_{0}\text{n} \longrightarrow ^{210}_{83}\text{Bi} \xrightarrow[\text{210Bi, } \beta^-]{\text{5.01 days}} ^{210}_{84}\text{Po}$

  (5-10 ppm – in nuclear grade lead
   1-3 ppm - high-purity specifications)

- **208Pb neutron capture :** $^{208}_{82}\text{Pb} + ^{1}_{0}\text{n} \longrightarrow ^{209}_{82}\text{Pb} \xrightarrow[\text{209Pb, } \beta^-]{\text{3.25 hours}} ^{209}_{83}\text{Bi}$

  (52.4% in nat. Pb)

  $^{209}_{83}\text{Bi}(\text{from above}) + ^{1}_{0}\text{n} \longrightarrow ^{210}_{83}\text{Bi} \xrightarrow[\text{210Bi, } \beta^-]{\text{5.01 days}} ^{210}_{84}\text{Po}$

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While α particles are easily shielded outside the body, ^{210}Po is highly volatile at LFR temperatures (400–500°C) $\Rightarrow$ it can enter the cover gas as an aerosol, posing a major **inhalation risk during maintenance or waste processing**.

^{210}Po-bearing waste are challenging not only due to **radiological hazard** but also to the **significant thermal load** within the waste stream, as ^{201}Po is characterized by a decay heat of **~ 141 W/g** (~ 10 times higher than of ^{60}Co)

After 5 years of operation:

- ^{210}Po activity concentration in coolant: **~ 8 MBq/kg**

- Considering the lead mass of _3400 t_ (initial ALFRED design), ^{210}Po total activity in coolant _is_ **~ 2.8E+13 Bq (0.168 grame)**

~ 99.8% as PbPo (lead polonide) and **~ 0.2%** as **volatile elemental Po**

PbPo has a very low volatility, and it decomposes at >600°C

Despite the low volatility of PbPo, Po still reaches the cover gas through the formation of aerosols and the evaporation of PbPo molecules
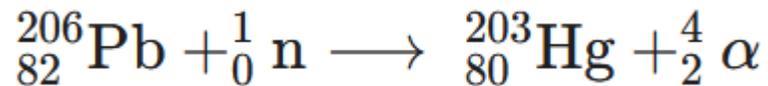
Po-210 Activation in Lead Coolant

Bq/kg vs time, days
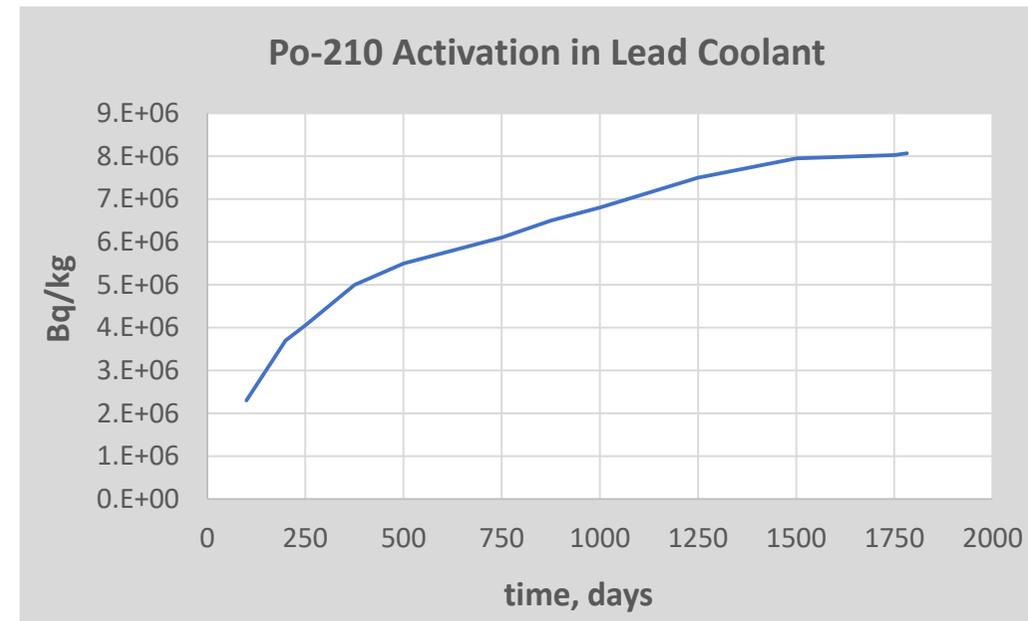
Considering only the fraction of volatile elemental Po in lead $\Rightarrow$ the amount with **high potential to be released in cover gas is ~ 5.60E+10 Bq (0.337 mg)**
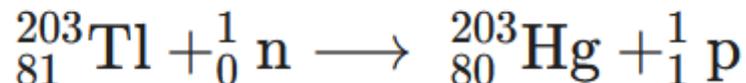
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❑ **^{203}Hg** is a significant concern for LFR waste management because, like polonium, mercury is a **volatile metal** $\Rightarrow$ can **escape into the cover gas** system

^{203}Hg generation in LFR coolant:

▪ **^{206}Pb (~ 24.1% in natural Pb):**

$$^{206}_{82}\text{Pb} + ^{1}_{0}\text{n} \longrightarrow ^{203}_{80}\text{Hg} + ^{4}_{2}\alpha$$

Half-life ($T_{1/2}$)	46.6 days
Decay mode	β^- (max. 0.212 MeV)
	γ (0.279 MeV)

▪ **^{203}Tl** impurities present in industrial lead or generated by activation of **^{204}Pb** (1.4% in natural lead)

$$^{203}_{81}\text{Tl} + ^{1}_{0}\text{n} \longrightarrow ^{203}_{80}\text{Hg} + ^{1}_{1}\text{p}$$

Main contributors to ^{210}Po and ^{203}Hg generation in Pb coolant

^{208}Pb (52.4% of nat. Pb)	contributes to ^{210}Po generation via ^{210}Bi
^{209}Bi (impurity) 5-10 ppm in standard nuclear grade Pb 1-3 ppm in high-purity specifications Pb	main contributor to ^{210}Po generation
^{206}Pb (25% of nat. Pb)	contributes to ^{203}Hg via direct α-ejection caused by fast neutrons
^{204}Pb (1.4% of nat. Pb)	contributes to ^{203}Hg via ^{203}Tl
^{203}Tl (impurity)	contributes to ^{203}Hg

Because Polonium tends to adhere to the metallic impurities ("dross"), the filters and cold traps used for coolant purification become α-active waste, requiring special handling compared to standard beta-gamma waste

RNs sources:
structural materials corrosion/erosion

LFRs generate **solid oxides** and **metallic impurities** (dross) in lead coolant

❑ Alloying elements (Fe, Cr, Ni, Mn, Ti) dissolve or erode into the lead coolant

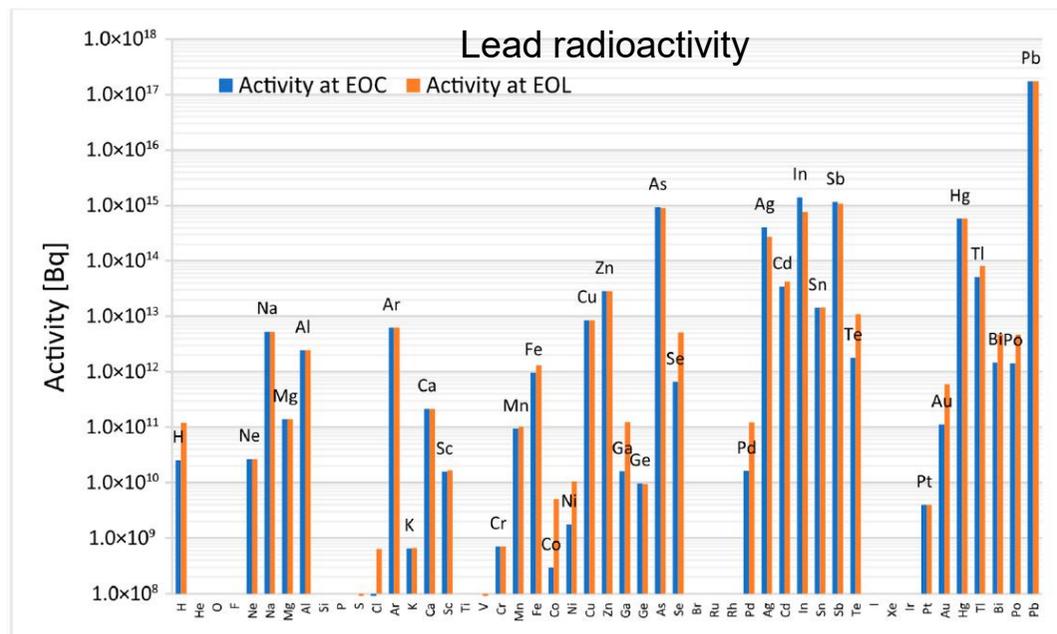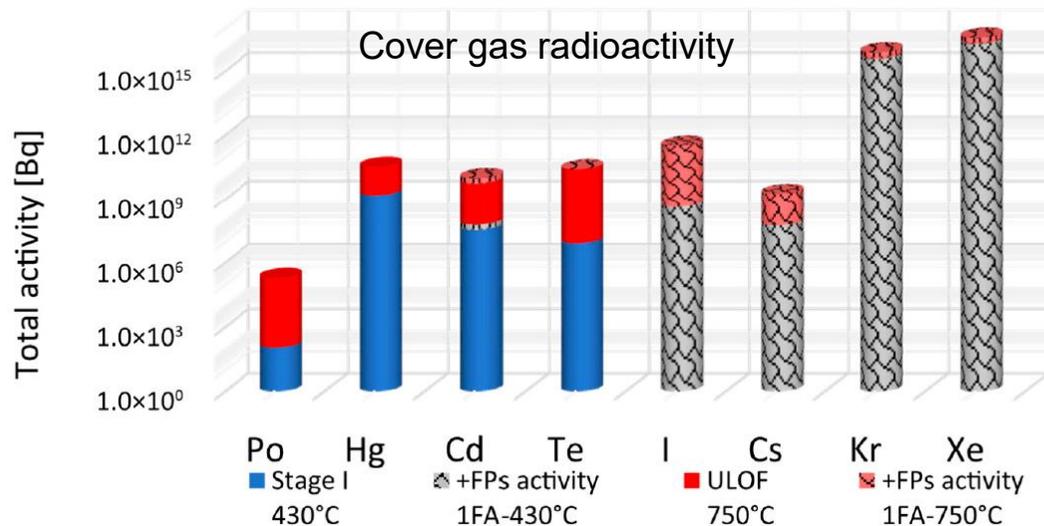❑ As these elements circulate through the high-neutron flux of the core, they capture neutrons and become radioactive

Primary gamma-emitters (from 316LN and/or 15-15Ti)				
RN	**Parent Isotope**	**Half-life ($T_{1/2}$)**	**Radiation Type / Energy (MeV)**	**Significance**
^{54}Mn	^{54}Fe (n,p) or ^{55}Mn (n,2n)	312.3 days	γ (0.834)	Major dose contributor. Manganese is highly soluble in lead and very active
^{60}Co	^{59}Co (n,γ)	5.27 years	γ (1.17 / 1.33)	Long-term source of high gamma radiation in primary components
^{59}Fe	^{58}Fe (n,γ)	44.5 days	β^- (max. 0.466), γ (1.099 / 1.292)	Short-term contributor to coolant activity
^{51}Cr	^{50}Cr (n,γ)	27.7 days	γ (0.32)	Formed from the activation of the protective oxide layer
^{58}Co	^{58}Ni (n,p)	70.8 days	γ (0.811)	Result of Nickel leaching/dissolution into the lead
^{46}Sc	^{46}Ti (n,p)	83.8 days	β^- (max. 0.36), γ (0.889 / 1.120)	^{46}Sc presence in the lead filters is a direct indicator of cladding erosion

Radioactivity of lead coolant and cover gas

After 40 years of irradiation (for lead mass: 3400 t):

➤ coolant **total activity** ~ **1E17 Bq**

- **over 97%** attributed to Pb radionuclides, mainly ^{207m}Pb ($T_{1/2}$ = 0.8 s)

Lead radioactivity

EOC – 3 years / EOL – 40 years

*A. Ivan et al., 2025, https://doi.org/10.3390/jne6030036*

Cover gas radioactivity

- ^{210}Po, ^{203}Hg, $^{113m/109}$Cd, ^{121}Te can contribute significantly to potential radiological risks as these elements **may volatilize** at elevated temperatures, increasing the radioactivity inventory of cover gas

❑ Impurities like lead oxide (**PbO**) can block coolant channels, while **activated corrosion products** like ^{54}Mn and ^{60}Co increase the radiological dose

❑ To prevent deterioration of hydrodynamic conditions in LFRs there is need for:

- **rigorous control of dissolved oxygen in lead (optimum level: $10^{-8} - 10^{-6}$ wt%)**

- **purification of molten lead and cooling circuit**

- **cover gas purification (H-2, H-3, Po, Hg, I, Ar, Kr, Xe)**
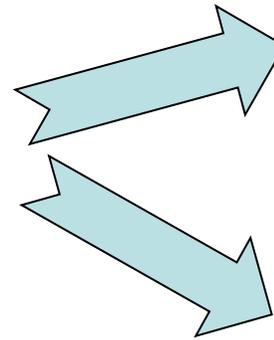
too low O_2 content $\Rightarrow$ steels dissolve into the lead (corrosion)

too high O_2 content $\Rightarrow$ PbO precipitates, forming solid slag

Need	Technical solutions	Effects	Radioactive waste generated by cover gas purification
Oxygen control	- gas-phase oxygen control (injecting a mixture of **Ar/H$_2$)**	Injected H$_2$ can undergo isotopic exchange with ^{3}H generated by ternary fission and (n,α) reactions	- filters for **HTO vapors** (molecular sieves or desiccant dryers)
		The **gas flow enhances the evaporation of ^{210}Po and ^{203}Hg** from the lead surface	- Filters for ^{210}**Po and** ^{203}**Hg** retention (HEPA, activated charcoal beds, cryogenic traps, or specialized liquid metal "scrubbers" using a different metal to amalgamate the mercury …)
			⇒ **Spent filters** used to "scrub" the gas before it is recycled or vented are **high-activity alpha and gamma wastes**
	- solid-phase oxygen control - PbO mass exchangers - *placed in restricted areas of the circuit (cavity side)*	The mass exchanger acts as a physical filter and a chemical trap, making it a very "concentrated" waste source	**Spent mass exchangers contaminated with Pb, ^{210}Po, and other gamma emitters**

❑ **purification of molten lead and cooling circuit**
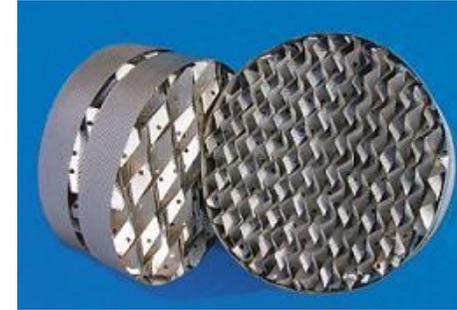
- ▪ Cold traps: oxides and metallic impurities (Fe, Cr, Ni, Mn…) precipitate and are captured on specific filters:
  - ○ wire gauze with a regular pattern of fibers made of metallic materials, carbon or other materials resistant to the lead
  - ○ granular materials and cermet

➢ **removed as ILW**

➢ **spent filters inventory:**

- ○ **RN from Pb impurities activation:** ^{122}**Sb**, ^{124}**Sb**, ^{76}**As**, ^{24}**Na**, ^{65}**Zn**, ^{115}**Cd**, ^{110m}**Ag**, ^{114m}**In**, ^{197}**Hg**, ^{203}**Hg** - **T$_{1/2}$< 250 d**
- ○ **neutron activation of Bi and of ^{208}Pb: ^{210}Po (138 days)**
- ○ **activated corrosion products: ^{51}Cr (27.7d), ^{54}Mn (312d), ^{55}Fe (2.7y), ^{63}Ni (100y) and ^{60}Co (5.2y)**
- ○ **fission products: ^{137}Cs (30.17y), ^{90}Sr (28.6y), ^{106}Ru (368d), and radioisotops of I, Xe and Kr**
- ○ **^{3}H (12.28y)**

Managing **210Po** is a top priority due to its **high alpha-radiotoxicity** and **volatility**

➢ Chemical form of Po after generation via neutron activation is predominantly **PbPo (Lead Polonide)**

   (*the Gibbs free energy for the formation of PbPo is highly negative* $\Rightarrow$ *the reaction is very favorable*)

➢ The estimate that **~99.8% exists as PbPo** and **~0.2%** exists as **volatile elemental Po** is a conservative safety assumption used for source term calculations

➢ **PbPo** has a **very low volatility, and it decomposes at >600°C**

   ▪ Despite the low volatility of PbPo, **Po still reaches the cover gas** through the **formation of aerosols** (microscopic droplets) and the **evaporation of PbPo** molecules

   ▪ PbPo can still evaporate or form **volatile hydride (H_2Po) if exposed to steam** (e.g., in a SGTR accident), leading to a release rate proportional to its concentration in the melted Pb

➢ Po can be efficiently extracted from liquid lead by **alkaline extraction** with **molten hydroxide mixtures** (S. Heinitz et al., 2010, doi:10.1016/j.jnucmat.2011.03.043)

   ▪ Po exhibits amphoteric behavior and can be extracted into the salt phase as **sodium polonide (Na_2Po)**.

❑ Components that are removed from the primary circuit for maintenance (i.e. reactor coolant pumps, steam generators, sensors ….) has to be cleaned by residual lead

▪ **Chemical decontamination**

    ○ Using organic-oxidizing mixture such as H_2O_2 - for lead oxidation (PbO) and CH_3COOH to form **lead acetate - highly soluble in water**

    ○ **Ultrasonic agitation** - the "cavitation" effect helps the acid penetrate into narrow gaps enhancing the decontamination efficiency

        ➤ **Liquid radioactive waste** contaminated with $Pb(CH_3COO)_2$ and activation/fission products

▪ **Heat treatment and hot inert gas jet blowing** (to allow lead remelting and its draining) combined with **vacuum distillation**

    ○ Pb is evaporated (end recovered on cold traps), leaving behind a residue of **concentrated polonides and oxides**

        ➤ **Solid residues** that can be easier managed than liquid waste

    ➤ Chemical decontamination may still be needed $\Rightarrow$ **smaller volume of secondary liquid waste, with lower radioactivity**

❑ To facilitate the **licensing of the ALFRED** construction on the RATEN ICN site, it is essential to **develop and validate comprehensive strategies** for the **management of RW and SF.**

▪ **Aqueous liquid waste generated during ALFRED operation:**

    ○ **largely similar to that of thermal reactors – with particularity of Pb contamination**

    ○ technologies developed in the Radioactive Waste Treatment Plant (STDR) of RATEN ICN Pitești may be adapted to manage specific liquid RW

        • **membrane processes such as microfiltration, nanofiltration, reverse osmosis – have potential to be applied for liquid RW**

        • **ion exchange processes using inorganic exchangers**

        • **solidification of solids/spent IEXs:**

            ✓ **by cementation, where applicable**

            ✓ **geopolymers**

▪ **Organic liquid waste:**

    ○ **distillation** – for organic fraction recovery and reuse (i.e. for liquids generated by decontamination of items contaminated with Pb) $\Rightarrow$ residues conditioning in cement based matrices or geopolymer

    ○ **direct conditioning** - cement / geopolymer

- **Solid waste from ALFRED operation**

  - **typical waste**, similar to solid waste generated by a thermal reactors:
    - glass, textile, paper, metal
    - existing treatment and conditioning technologies can be applied
      - ✓ decontamination, compaction, cementation

  - **LFR particular LIL solid waste, generated from:**
    - **lead purification system**
    - **cover gas purification system**
    - **cooling system**
      - ➢ **treatment & conditioning technologies need to be developed and implemented, appropriate for:**
        - **the material type (generally filters) and the radionuclides content**

When dross-type waste or filters are encapsulated in cement/glass or geopolymer matrices, the **decay heat** generated by ^{210}Po must be taken into account **to avoid degrading the matrix** during the first months of storage (when activity is at its peak)

Techniques for processing and storage the operational liquid and solid RW are nowadays available.

Improved methods may be developed in future years, but new techniques would only represent an evolutionary improvement over the current methods.

- **largely similar to the waste resulting from the decommissioning of the CANDU reactor**
  - **reactor vessel, safety vessel, inner vessel, steam generator, grids, I&C devices etc.**
  - **cleaning for lead impurities on their surface may be necessary**
- The difference – **the coolant** - requires **finding a viable management solution** for irradiated lead following its discharge from reactor.
- **Inventory**

  While ^{210}**Po** accounts for most of the radioactivity during the **initial years**, due to its **short half-life (138-day)**, the **primary challenge for final disposal** lies in the **isotopes that remain active for hundreds or even millions of years:**

  - Pb isotopes: ^{205}**Pb** (17.3 million y), ^{210}Pb (22.2 y)
  - Impurities activation: ^{108m}**Ag (418 y)**, ^{194}Hg (444 y), :
  - Activated Corrosion Products: ^{63}Ni (100y), ^{124}**Sb** (60.2 y), ^{60}**Co** (5.27 y), ^{54}**Mn** (312 days)

  A few days after shutting down the reactor, the gamma activity of the coolant will be determined mainly by ^{110m}Ag, ^{124}Sb, ^{60}Co.

Management of irradiated lead

- Irradiated lead can be **collected directly in high corrosion resistance containers** for geological disposal
  - **by cooling, the irradiated lead become solid matrix which immobilizes the RNs $\Rightarrow$ ensuring a very low release rate under disposal conditions**
  - **Drawbacks for direct disposal:**
    - ✓ **Discharging the entire inventory of lead** directly into geological disposal containers would create a **massive volume of HLW**
    - ✓ **Lead is hazardous chemical**
    - ✓ **the decay heat** from ^{210}Po and activated corrosion products is substantial
    - ✓ **pressure buildup** as Helium gas (α particles) is generated by ^{210}Po decay
- **Alternative**
  - **storage** in dedicated tank for several years to let ^{210}**Po and** ^{124}**Sb decay;**
  - **separation/purification** for high-activity radionuclides extraction from the lead (using vacuum distillation or chemical extraction)
    - ➢ only the **concentrated residue is conditioned** and **geological disposed** into high-corrosion-resistant canisters for disposal
    - ➢ the bulk of the **lead is reused** in a new LFR or **stored as LLW** until it meets clearance levels for **industrial recycling** (if ^{205}Pb is below the exception level)

Decontamination for recycling can be considered depending on the amount of ^{205}Pb formed during lead irradiation

Management of ALFRED spent fuel

LFR SF: - higher activity of Pu, Np and Cm

- higher heating rate generated by actinides

Adequate strategy for handling significant thermal loads has to be developed

❑ The SF extracted from the core of an LFR has a temperature of **~ 400–550°C**, while the water in the pool is maintained **below 50°C**

➢ the **SF has to be cooled down** before transferring it to the water storage pool to avoid large temperature gradient that affect the cladding integrity

❑ The SF extracted from the core and loaded in the cover gas into transfer canister contains **residual lead that has to be removed before under water storage**

➢ **Integrated decontamination has to be developed:** Before entering long-term storage, the lead film must be removed.

o since the fuel extracted in a transfer cell, a **decontamination step should be performed in this cell**, before encapsulating the clean SF into the wet storage canister

Residual lead removal from SF

- ❑ **Chemical decontamination**
  - o organic-oxidizing mixture such as **H_2O_2** - for lead oxidation (PbO) and **CH_3COOH** to form **lead acetate - highly soluble in water** may be used combined with **ultrasonic agitation** to enhance the decontamination efficiency
    - ➤ **Liquid radioactive waste** contaminated with $Pb(CH_3COO)_2$, ^{210}Po and activation/fission products
      - ➤ the organic fraction may be recovered for further reuse by distillation
      - ➤ residues has to be treated as ILW and may be vitrified or conditioned in a ceramic matrix
    - ➤ **Due to the volume and complex composition of the secondary liquid waste generated, chemical decontamination of SF should be avoided**
- ❑ **Alternative decontamination techniques**:
  - o **hot gas jet blowing** - to facilitate draining the residual lead
  - o **vacuum distillation** - Pb is evaporated end **recovered on cold traps**

Storage challenges

❑ Two routes may be considered for ALFRED spent fuel:

Option 1 - closed fuel cycle:

wet storage – dry storage

reprocessing ⇒ HLW to be geological disposed

partitioning and transmutation

Metallic fuel reprocessing technology is available in France – need to be adapted for LFR MOX fuel

Option 2 - open fuel cycle:

wet storage – dry storage

– SF geological disposal together with CANDU SC

❑ Criticality control: The storage geometry must ensure sub-criticality even in the event of accidental flooding

❑ Long-term monitoring: Sensors for Helium buildup (from alpha decay) must be part of the storage R&D

❑ Decay heat threshold for moving the spent fuel assembly from wet storage to a dry storage facility is a critical balancing act between thermal safety (protecting the cladding) and operational logistics

❑ **Wet storage** – designed to ensure the reduction of fuel activity and thermal load (short-lived radioisotopes decay).

    o   in an adjacent reactor pool, designed for the entire life-time

❑ **Dry storage**

    o   specific requirements due to the **higher disintegration heat** and the **higher radiation fields** compared to CANDU SF

      • higher radiation levels require more **advanced shielding of storage systems**

   • higher temperature needs a **higher cooling rate**

       Dry storage of CANDU spent fuel - natural cooling

       MOX fuel generated by LFR - probably will need forced cooling

❑ **Option 1. Closed fuel cycle** – ALFRED **spent fuel is sent for reprocessing** in the country of origin (for example, the La Hague - France reprocessing plant receives spent fuel sent by foreign electricity companies)

- o U, Pu and the main minor actinides (Np, Am and Cm) - separated to be used in advanced fuel cycles

- o the conditioned radioactive waste generated by reprocessing (mainly containing fission products) will be returned to Romania for final disposal

  ➢ **What has to be solved**: safe storage until geological disposal will be available in Romania (foreseen for 2055)

  ➢ **Implications**: the volume and inventory of the vitrified HLW have to be considered in the geological disposal designing (currently intended only for CANDU SF and other long-lived waste from the operation and decommissioning of Cernavoda NPP).

❑ **Option 2. Open fuel cycle** - ALFRED spent fuel is disposed off in Romania, together with CANDU spent fuel and the long-lived waste generated by Cernavoda NPP

- ALFRED SF volume - negligible compared to the volume of SF generated by 4 CANDU units (considered in the current geological disposal reference concept)

- ALFRED SF activity – contributes significantly to the inventory

  - **Geological disposal concept** has to take into account from the beginning the additional ALFRED SF inventory.

  - **Repository design** (*Canadian design is considered as reference in the current strategy*) – needs some **changes due to the limitations related to the ALFRED fuel assembly temperature and subcriticality conditions** (geometry/size of disposal galleries or wells, buffer, etc.).

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Conclusions
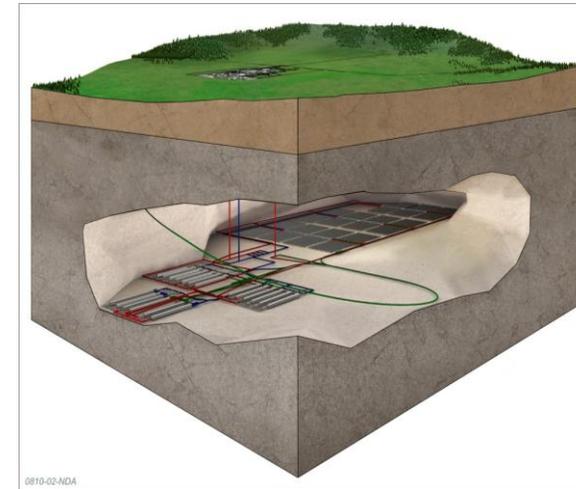
❑ The impact of spent fuel and radioactive waste management **is a key issue of the licensing process**

❑ It is crucial **to address the back end of fuel cycle from the design phase** to ensure **accurate inventory information on waste streams** are available for robust planning the waste management and development the needed technologies to manage the waste from the generation to disposal.

❑ LFR involves higher fuel burn-up with significant impact on the SF storage and reprocessing/disposal

❑ Lead used as coolant generate particular radioactive waste category and inventory

❑ Close collaboration with the designer is essential to:

  • define the specific radioactive waste streams generated by **techniques adopted for O$_2$ control and lead and cover gas purification**

  • **corelate the adopted option for SF discharge with the requirements for SF cleaning and storage (wet and dry)**

• As an attractive option to capitalize the value of the resources and to reduce the amount of high level waste, the **SF reprocessing option has to be carefully analyzed from the economic point of view**.

Thank you for your attention!