



**Committee on Radioactive Waste Management**

# **Radioactive waste from small modular reactors**

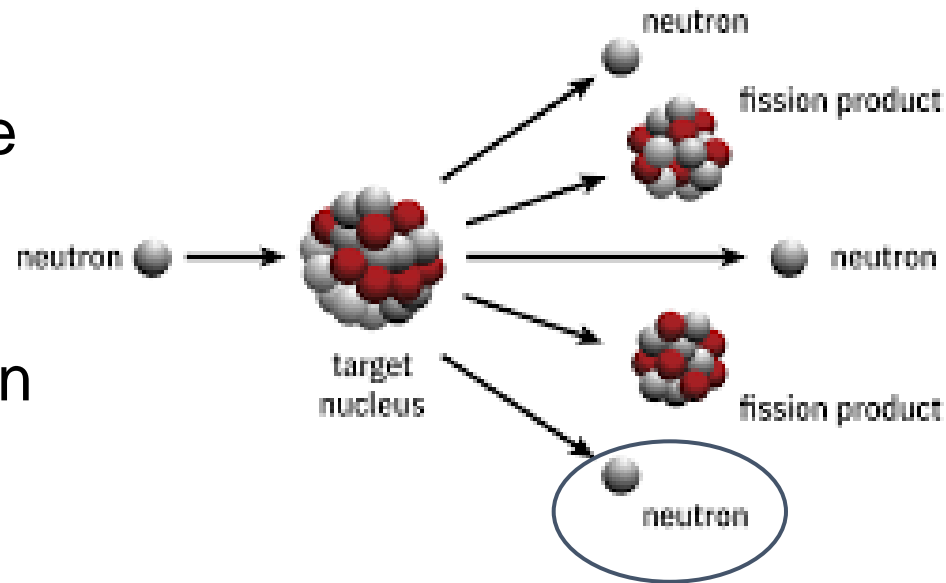
# Factors influencing how much waste is generated from a nuclear reactor

1. Reactor size (neutron leakage and component activation)
2. Fuel burn-up (radioactivity/radiotoxicity and decay heat of spent fuel generated)
- (3. and 4.) Coolant / moderator type (volume of ILW generated)
5. Fuel type (governs necessity for reprocessing)

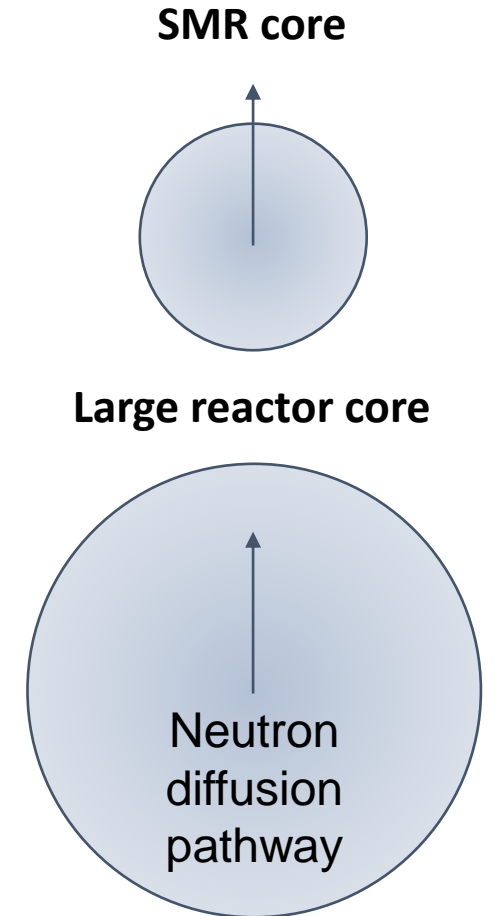
# 1. Reactor size (neutron leakage and component activation)

## Neutron leakage

- Neutron diffusion pathway is the same length for all thermal neutrons
- So a smaller reactor core has an inherently higher probability of neutron “leakage”
- Activation of: stainless steel, concrete, moderator materials (graphite, salts), shielding and neutron reflectors



**Nuclear fission**

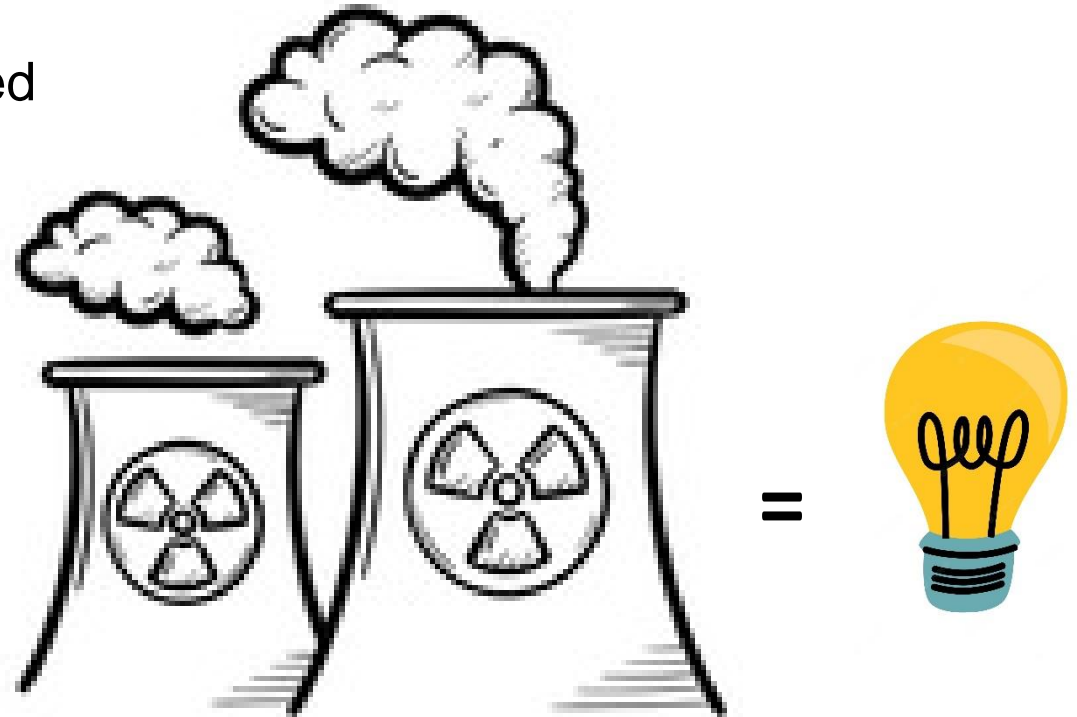
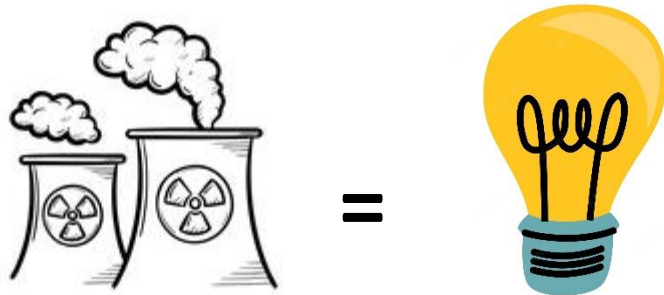


**Impact:** increased volume of short and longer-lived ILW (decommissioning wastes)

# 1. Reactor size: Neutron leakage = reactor inefficiency

## Comparison of small and large PWR with same fuel enrichment

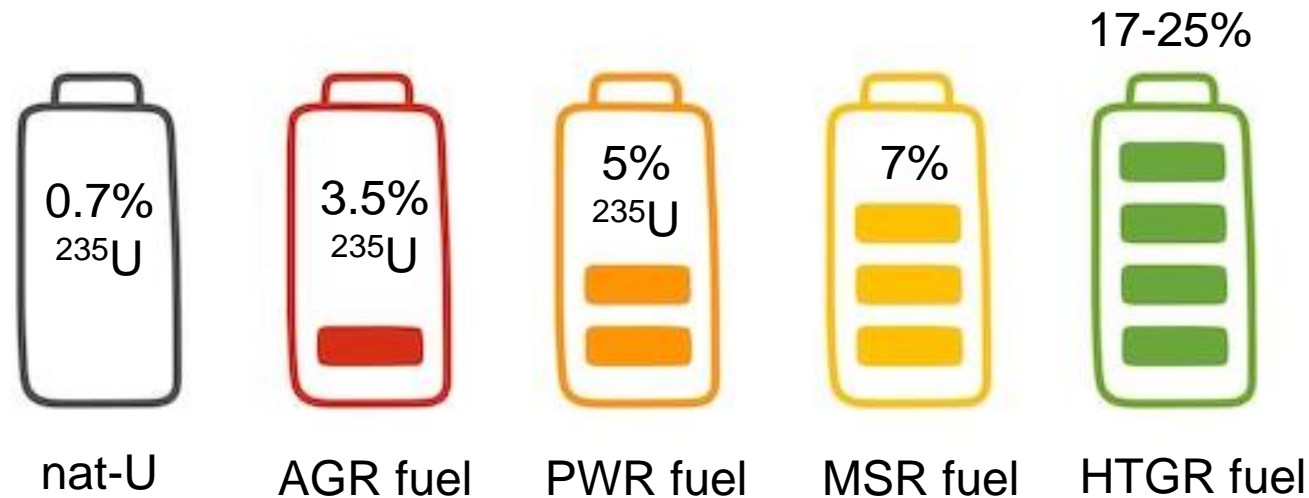
- Leaking neutrons mean that more fuel is required to generate a given amount of energy.
- More fuel = more spent nuclear fuel waste.



## 2. Increased fuel enrichment

### A greater fissile material content counteracts neutron leakage

- Most AMRs plan to use more highly enriched fuels
- Higher enrichment results in a greater content of fissile material in the spent nuclear fuel



**Impact:** The radiotoxicity of the spent fuel increases with enrichment. The probability of criticality is higher for highly enriched fuels, which may have an impact on storage and GDF footprint.

# 3. Coolant type

Water  
(pressurised)

Gas (CO<sub>2</sub>, He)

Liquid metal  
(sodium, lead,  
lead-bismuth)

Molten salt  
(alkali metal  
chlorides and  
fluorides)

# 3. Coolant type

Liquid metal  
(sodium, lead,  
lead-bismuth)

**Impact:** Potentially hazardous during decommissioning, large volumes of metal to manage and treat (e.g. Dounreay FBR)

## Liquid metal:

- Reactor should be built with decommissioning in mind
- Hazardous reactions with water, air oxygen (sodium), toxic (lead)
- Super phenix sodium fires
- Residual coolant that cannot be drained must be removed under inert atmosphere and treated (to NaCl)

Molten salt  
(alkali metal  
chlorides and  
fluorides)

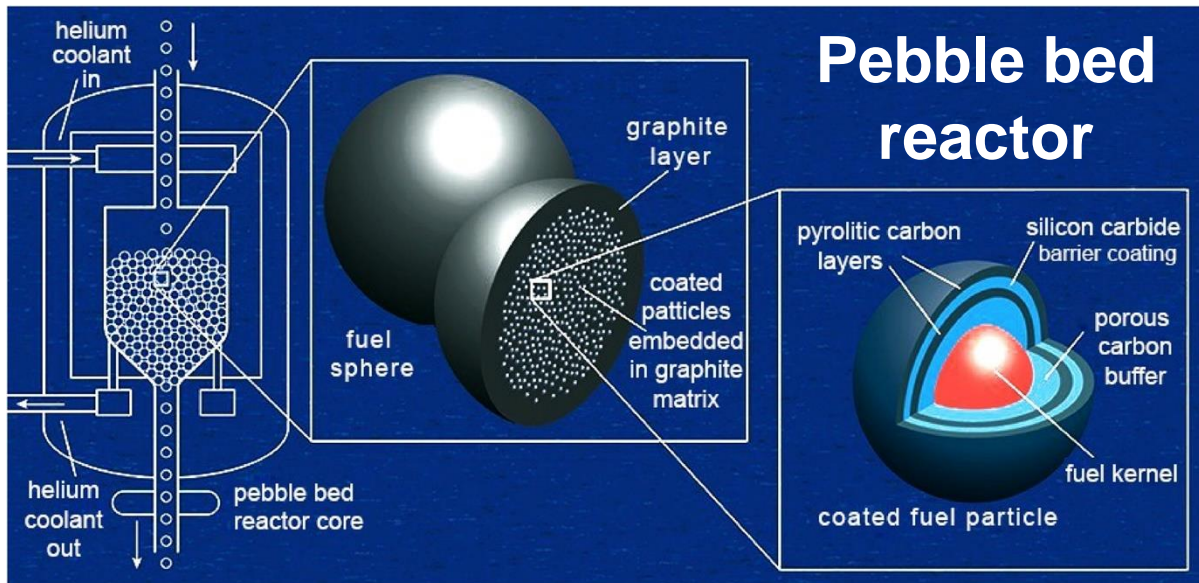
**Impact:** Chemically challenging wastes, large volume of salt and alkali

## Molten salts:

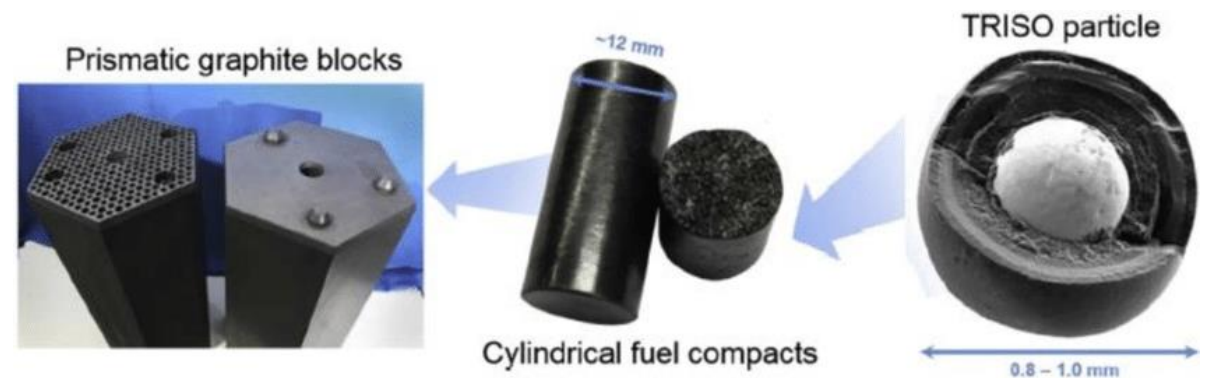
- Corrosive in-reactor, requires development of untested new alloys
- Fluoride salts can generate corrosive (e.g. HF) or explosive (e.g.  $H_{2(g)}$ ) by-products
- Experimental molten salt reactors have experienced difficulties in decommissioning

# 4. Moderator type

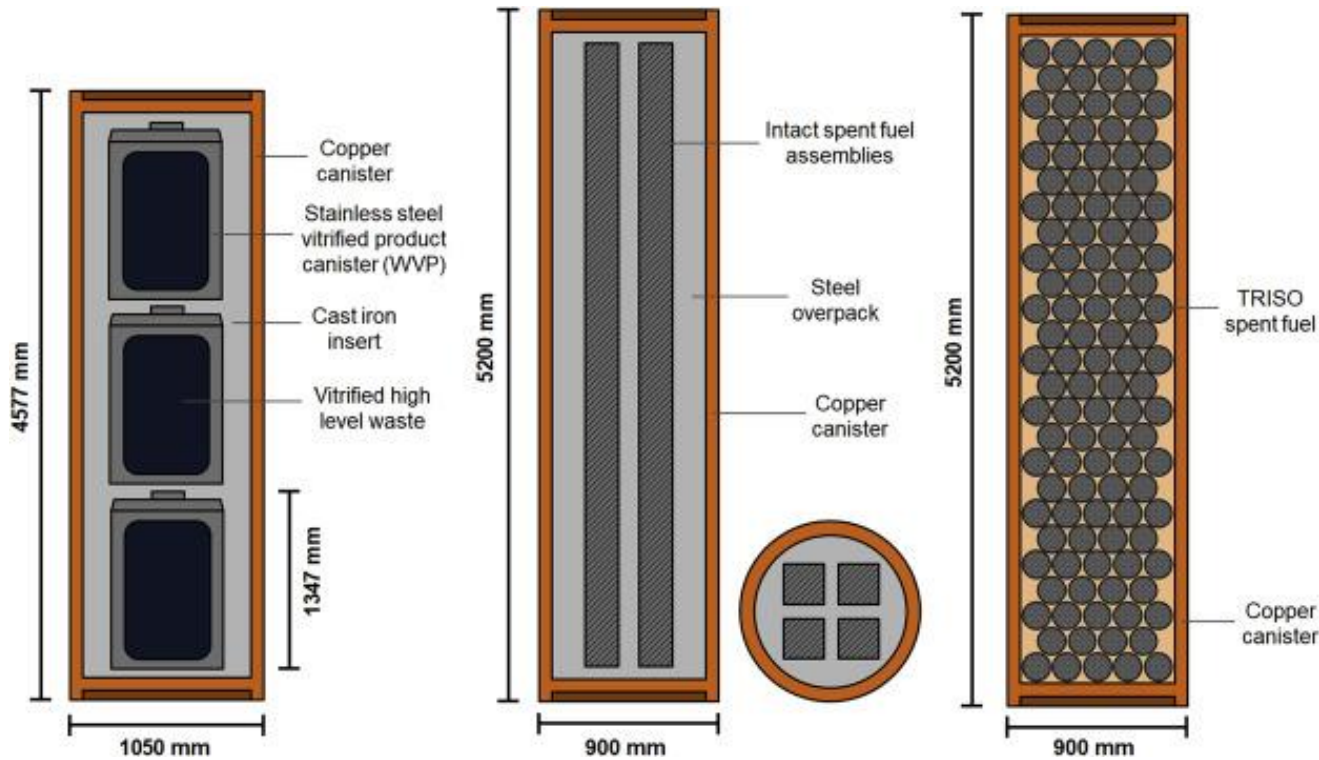
- **Fast reactors** do not require a moderator. Rely upon neutron reflectors = neutron activation of reflectors
- **High temperature gas-cooled reactors** will use a large amount of graphite (pebbles / prisms)
- Graphite also intrinsically present in the TRISO fuel (cannot be separated post-fission)



## Prismatic HTGR



# 4. HTGR graphite moderator

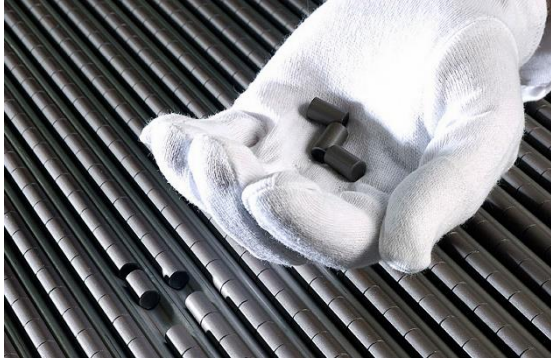


Dungan et al., *Energy*, **221**, 119826 (2021)

- No reprocessing (not possible to shear graphite from fuel kernels)
- Volume of spent fuel per unit energy is much larger (estimated 8 times when compared to large PWR)
- $^{14}\text{C}$  content of graphite may be too high for incineration
- May need to overpack, coat or encapsulate for disposal

**Impact:** Large volumes of graphite waste, some intimately mixed with spent fuel. Spherical nature of fuel / moderator results in large volume for disposal

# 5. Fuel types

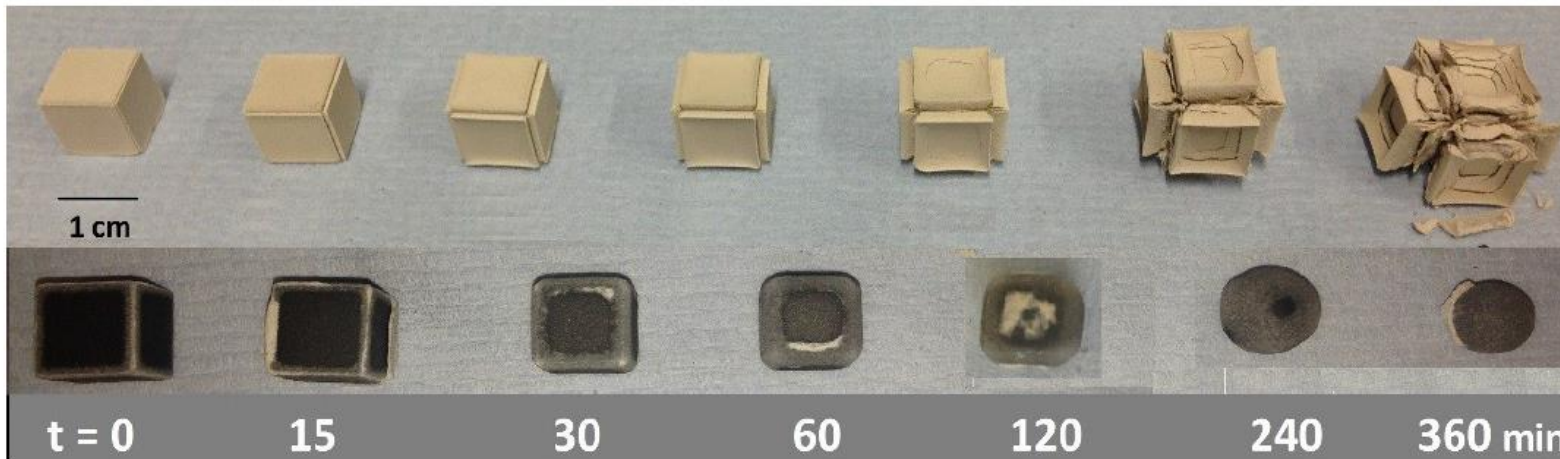


## UO<sub>2</sub> fuel:

- Chemically inert
- Does not require reprocessing prior to disposal, but can be reprocessed using aqueous routes
- Technically confident in the long-term behaviour in a GDF

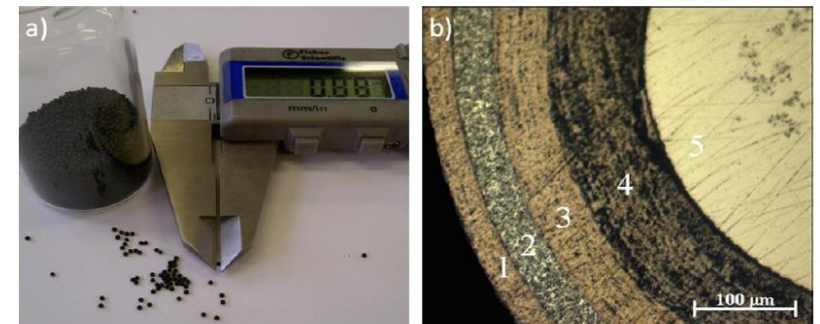
## UC / USi / UB / UN and metallic fuels:

- Chemically reactive
- Require reprocessing or treatment prior to disposal



## TRISO fuels:

- Layered fuel
- Difficult to separate fuel from graphite – no processing route



# 5. Fuel types



## Molten salt fuel:

- LiF /  $^{235}\text{UF}_4$  salt
- Requires electrochemical “pyro-reprocessing”
- Pyroprocessing is not well developed (not demonstrated at an operational nuclear scale)

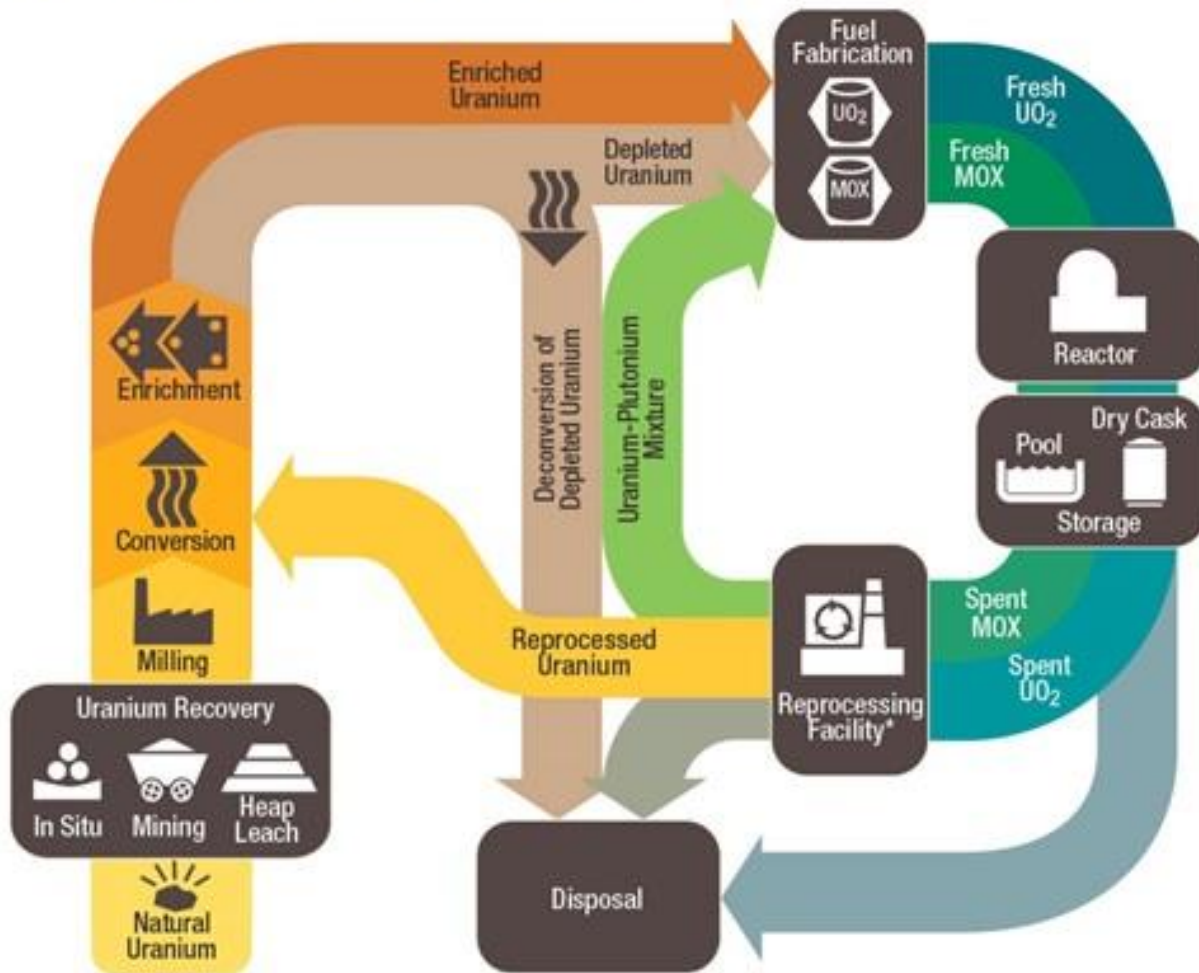
## Will require novel wasteforms for:

- Radio-Cs / Sr = glass?
- Lanthanide fission products = glass
- $^{99}\text{Tc}$  = glass?
- Radioactive noble metals
- Decommissioning wastes = cement?



# 5. Fuel types: Open or closed fuel cycle

## The Nuclear Fuel Cycle



**Reprocessing** is required to passivate most exotic fuel types and make them safe for disposal

- Aqueous reprocessing well understood
- Alternatives (pyroprocessing, voloxidation) still at low TRL

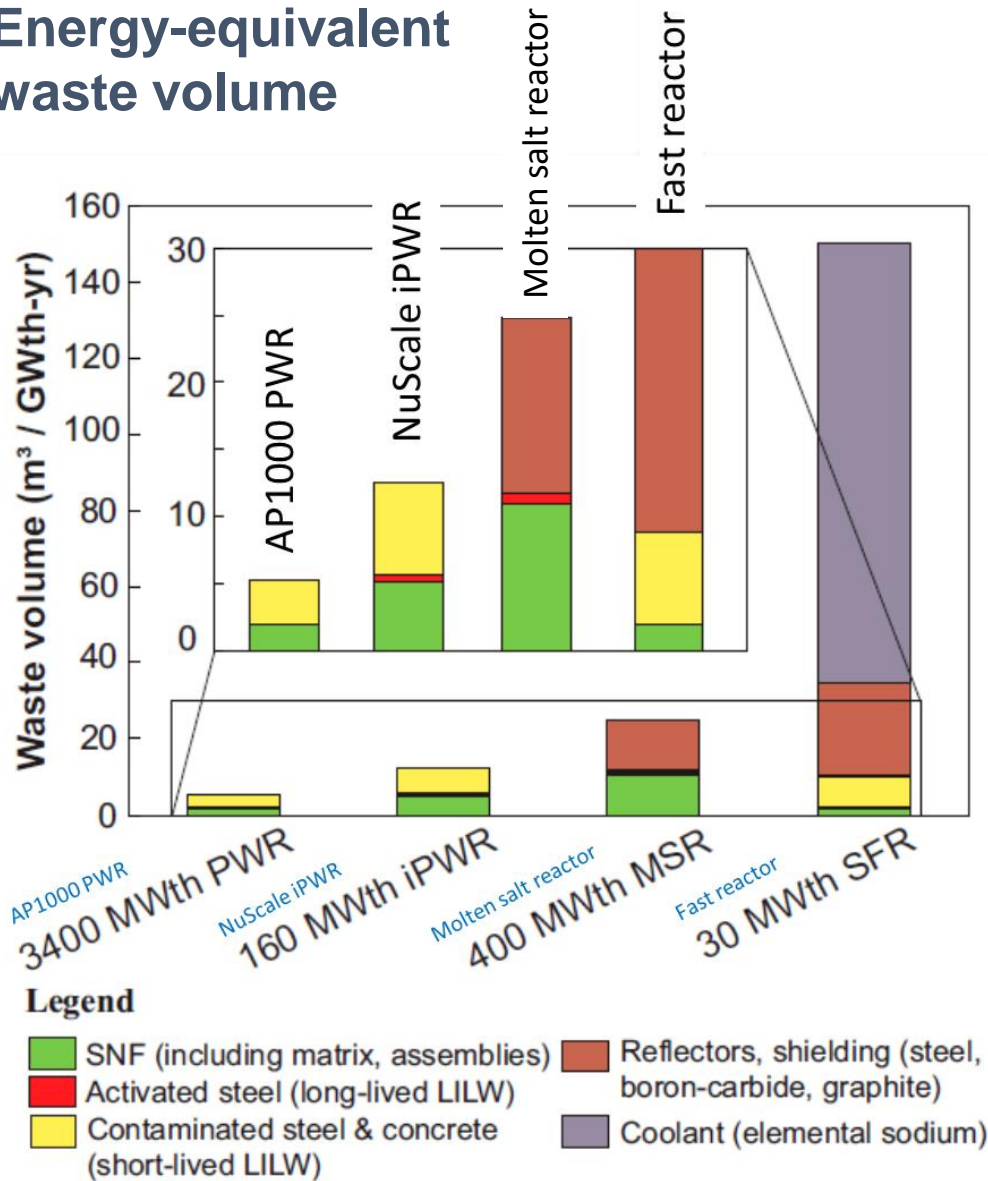
**Impact:** Reprocessing gives rise to a wide variety of waste types (HLW, ILW, LLW), some of which are yet to be innovated (hence their storage and disposability cannot yet be assessed)

**These are very generic considerations!**

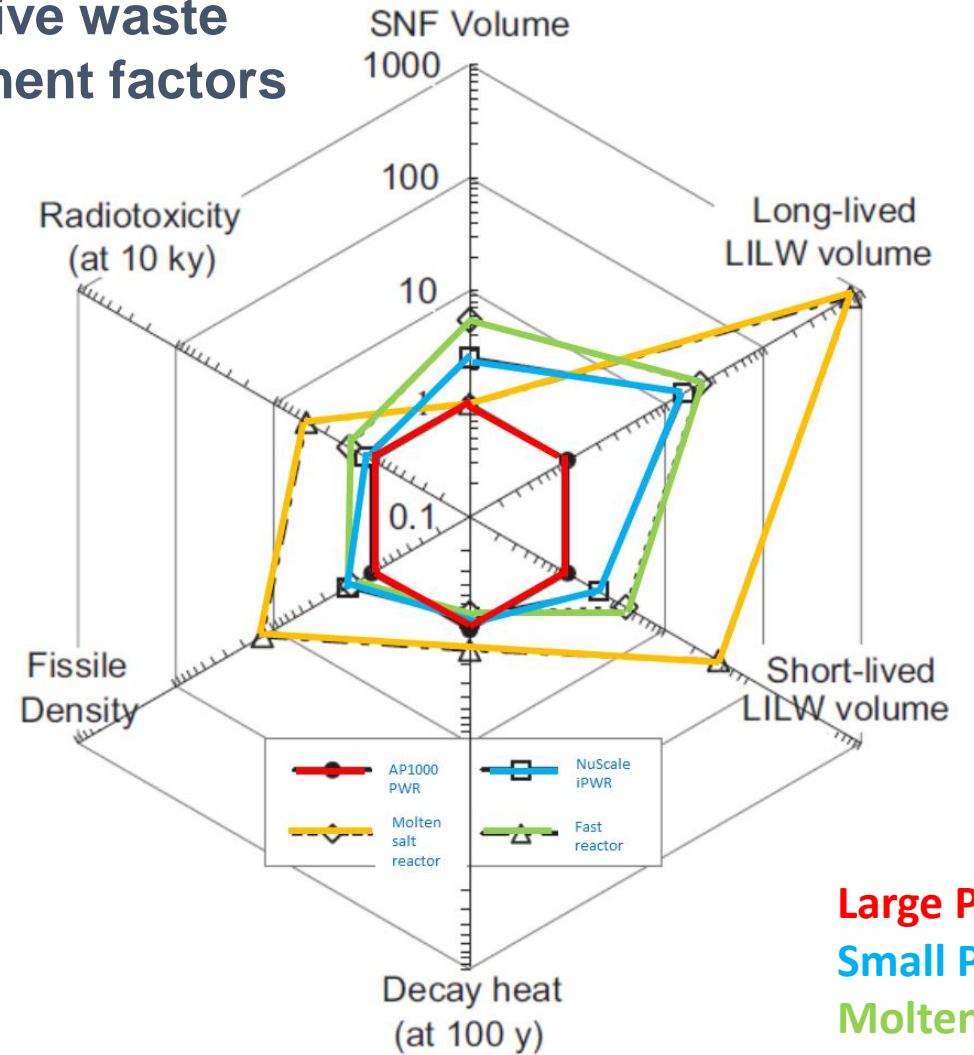
**Can only truly assess impacts on waste generation, management and disposal when the detailed designs are understood.**



## Energy-equivalent waste volume



## Radioactive waste management factors



Large PWR  
Small PWR  
Molten salt  
Fast breeder

- The choice of reactor type and design has significant bearing on the type and volume of waste generated
- Some designs are more advanced than others in terms of their “waste and disposability” technology readiness
- Most types of waste have been generated in the past (experimental reactors), but not without challenges
- It is difficult to truly assess the implications for radioactive waste management until detailed designs are made available