Nuclear waste from small modular reactors

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Small modular reactors (SMRs)

- Advanced reactors as SMRs
- SMRs <300 MW_{el} (~1000 MW_{th})
  - Capital investment ("economy of multiples")
  - Safety & proliferation
  - **Waste**
- Mass & radiotoxicity *vs.* composition: (geo)chemistry, re-criticality, heat
- SNF/HLW, long- & short-lived LILW
  - 3400 MW_{th} PWR
  - 160 MW_{th} NuScale iPWR
  - 400 MW_{th} Terrestrial IMSR
  - 30 MW_{th} Toshiba 4S

SMRs enhance neutron leakage

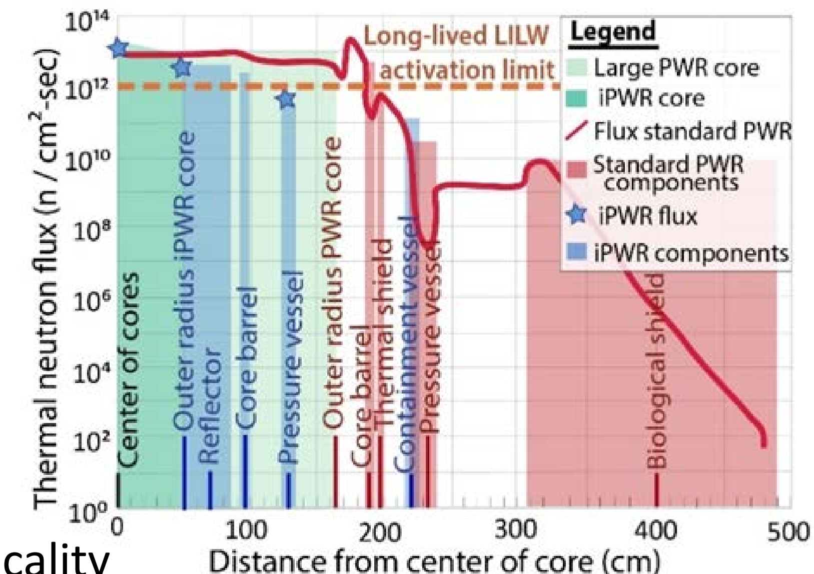
- Reactor power depends on neutron flux (**Φ**) and, in turn, the effective multiplication factor (***k***)

$$\boldsymbol{k} = \eta f p \epsilon \boldsymbol{P_{NL}}$$

- Probability of leakage ($P_L = 1 - P_{NL}$) depends on reactor radius & neutron diffusion length

$$P_L \sim \frac{1}{R^2}$$

- Reduces fuel burnup, incentives[1,2]:
  - Initial enrichment >5 wt% ^{235}U
  - Neutron reflectors
  - Non-water moderator (*e.g.* graphite)
- Implications for:
  - Spent fuel composition
    - → ^{239}Pu purity & proliferation[1];
    - → Decay heat, radiochemistry, criticality
  - Activated & contaminated LILW (reflectors, moderator, coolant)



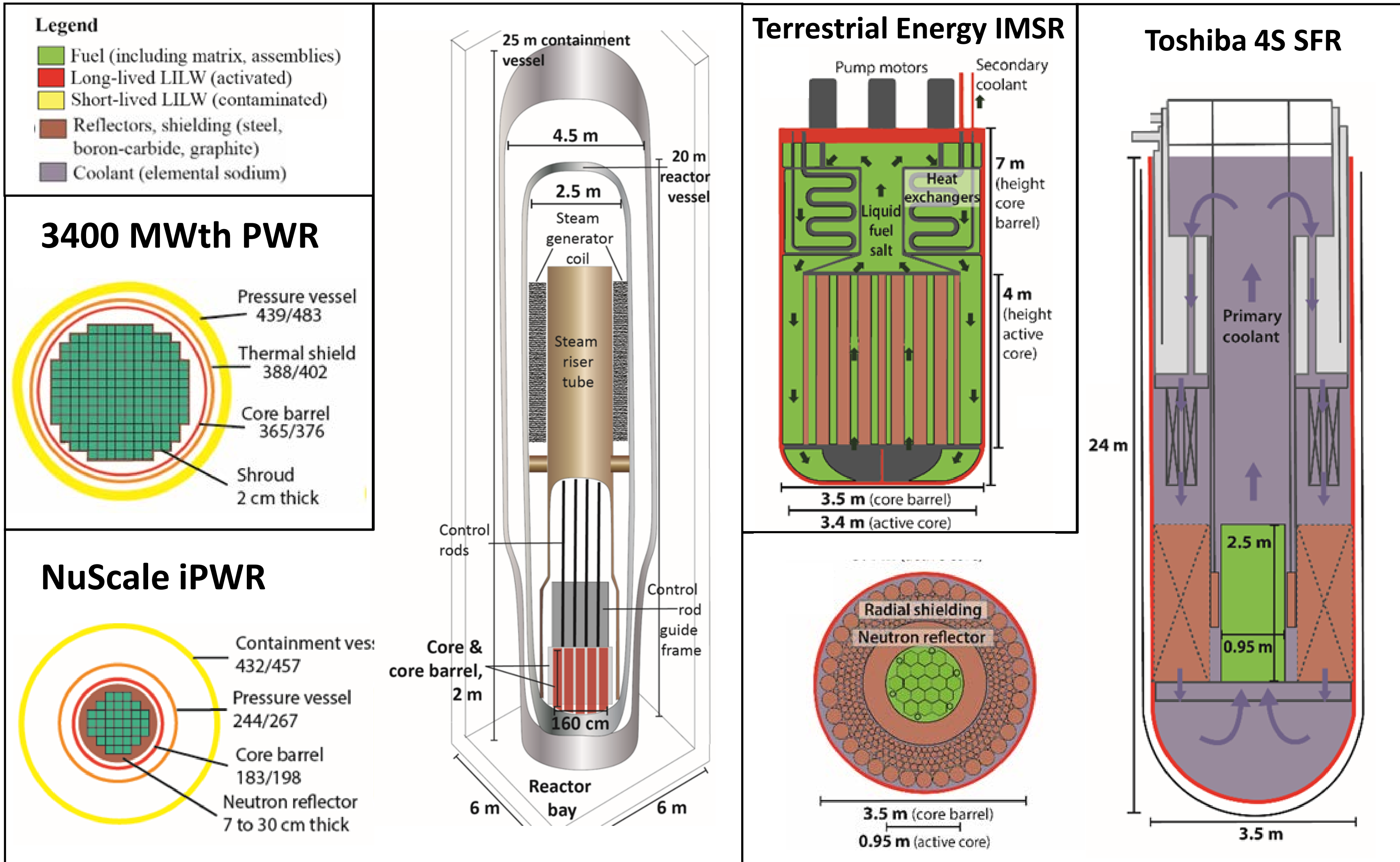
[1]Glaser, A. (2013). *Nuclear Technology* [2]Brown & Todowsow (2017). *Annals of Nuclear Energy*

Design overview (1)

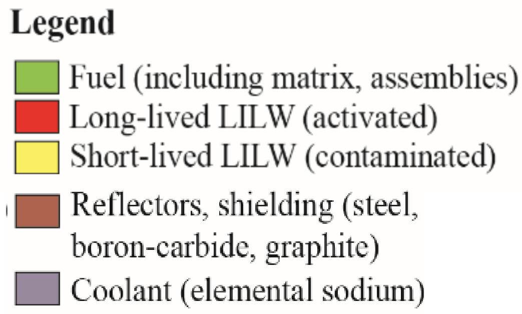
- Vessel and component lifetimes limited by corrosion (molten salt), radiation damage (graphite, fast neutrons)

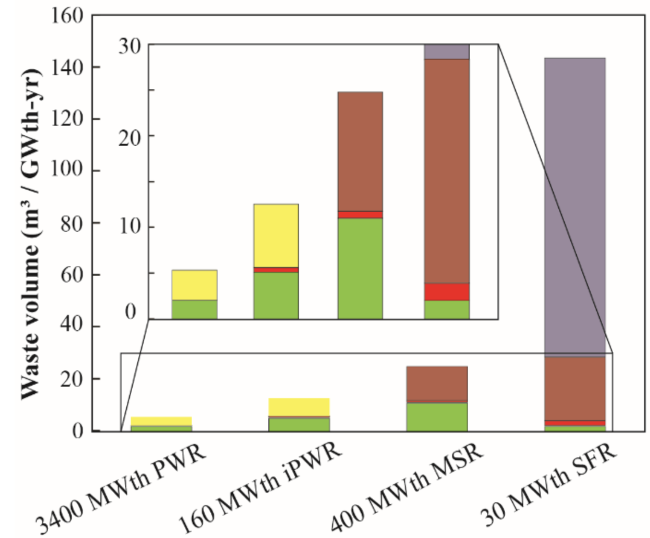
Reactor type	MW_{th}	Enrichment (%)	burnup (MWd/kg)	Vessel lifetime (yr)	Moderator	Coolant	Reflector	Shield
AP1000 (Westinghouse)	3400	4.8	60	60	water	water	water	
iPWR (NuScale)	160	5	34	60	water	water	steel	
IMSR-400 (Terrestrial Energy)	400	3	14	7	graphite	NaF, BeF_2, or LiF	graphite?	
4S-30 (Toshiba)	30	19	34	60	n/a	sodium	stainless steel	boron-carbide
4S-135 (Toshiba)	135	18	90	60	n/a	sodium	stainless steel	boron-carbide
Oklo (Oklo Inc.)	4	20	< 10	20	n/a	sodium	zirconium + stainless steel	boron-carbide
BN1200 (JSC/OKBM)	2800	13	112	60	n/a	sodium	beryllium	boron

…design overview (2)



Waste types





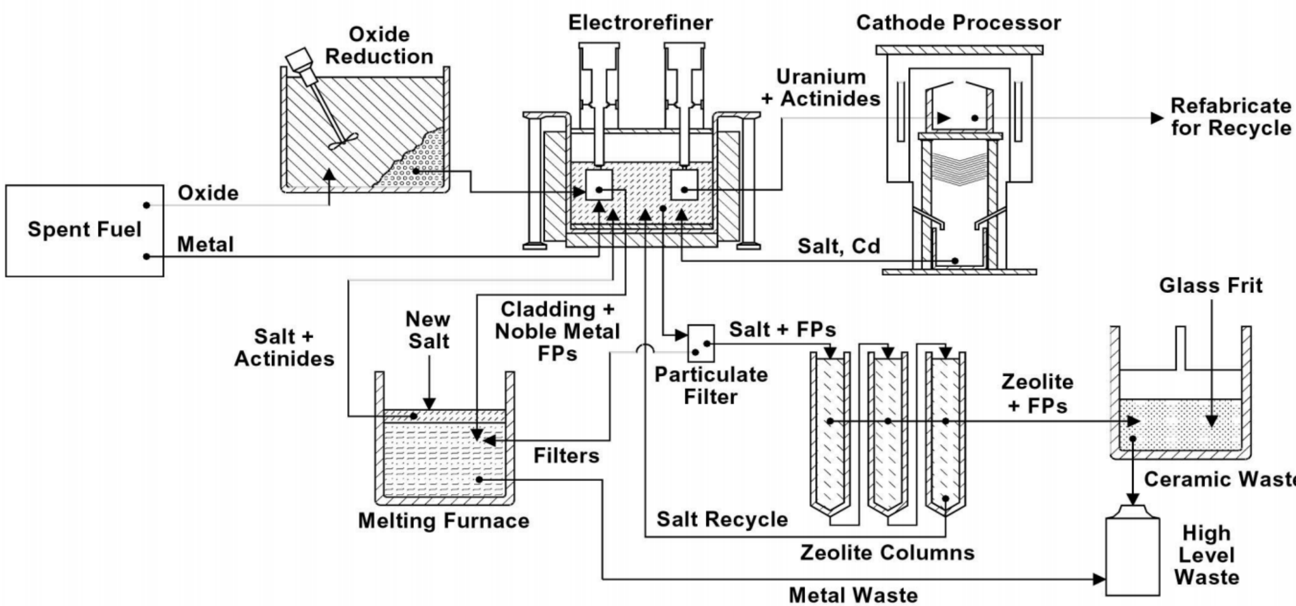
- Packaged waste volumes will be larger

Material	Nuclides*	Management	Disposal
Spent fuel	^{59}Ni, ^{129}I, ^{79}Se, ^{36}Cl, ^{14}C, ^{226}Ra (dose) ^{137m}Ba, ^{90}Y; ^{241}Am, ^{238}Pu (heat) ^{235}U, ^{239}Pu, ^{241}Pu (re-criticality)	Shielding, storage; **treatment & conditioning of sodium-bonded SFR fuel**	Deep repository, multiple barriers
Activated steel	^{54}Mn (0.85), ^{55}Fe (2.7), ^{60}Co (5.3) ^{93}Mo (4.0e3), ^{14}C (5.7e3), ^{94}Nb (2.0e4), ^{59}Ni (7.6e4), ^{99}Tc (2.1e5), ^{36}Cl (3.0e5)	SAFSTOR or shielding	Deep repository (cementitious)
Contaminated steel, concrete	Most of the above	Decontaminate (water)	Shallow burial
Molten salt	^{18}F (2.1e-4), ^{24}Na (1.5e-3), ^{51}Cr (7.7e-2), ^{59}Fe (0.12), ^{58}Co (0.19), ^{22}Na (2.6), ^{55}Fe (2.7), ^{60}Co (5.3), ^{3}H (12), ^{14}C (5.7e3)	Mitigate **corrosion**; convert to stable form (*e.g.* CaF)	Deep repository, multiple barriers
Sodium	^{24}Na (1.5e-3), ^{22}Na (2.6) ^{134}Cs (2.4), ^{137}Cs (30), & ^{60}Co (5.3)	Deactivate (**inert atmosphere**)	Shallow burial of NaOH?
Graphite	^{3}H (12), ^{14}C (5.7e3), ^{36}Cl (3.0e5)	Thermal treatment?	Deep repository

* Plus activation products formed from impurities

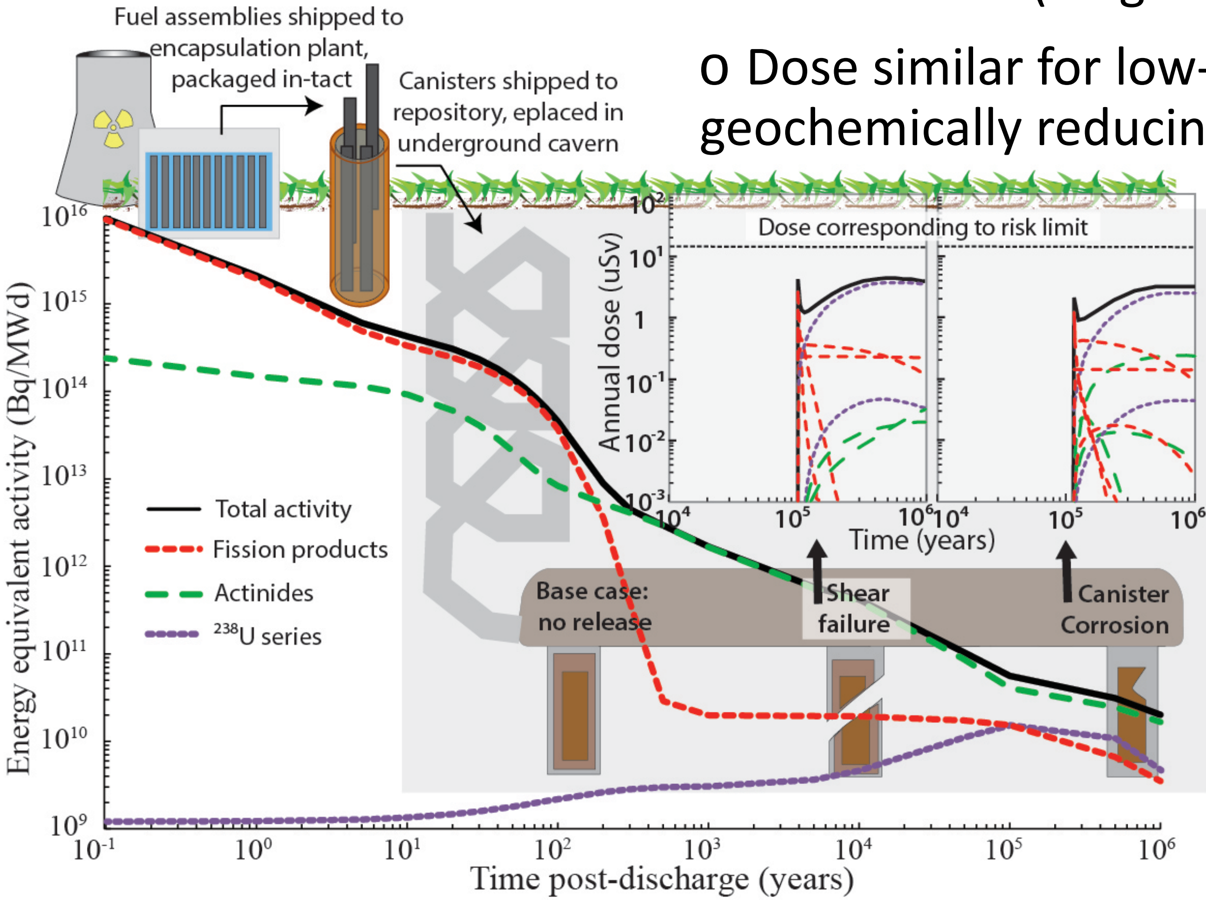
Treatment of non-UO_2 fuels

- Pyroprocessing or electrometallurgical treatment (below)
- Fluoride volatility processing ($UF_4 \rightarrow UF_6$)
- Dual use technologies (proliferation)
- Additional waste streams (neglected from estimates)
- Followed by conditioning into stable waste form



Storage, transportation, packaging & disposal

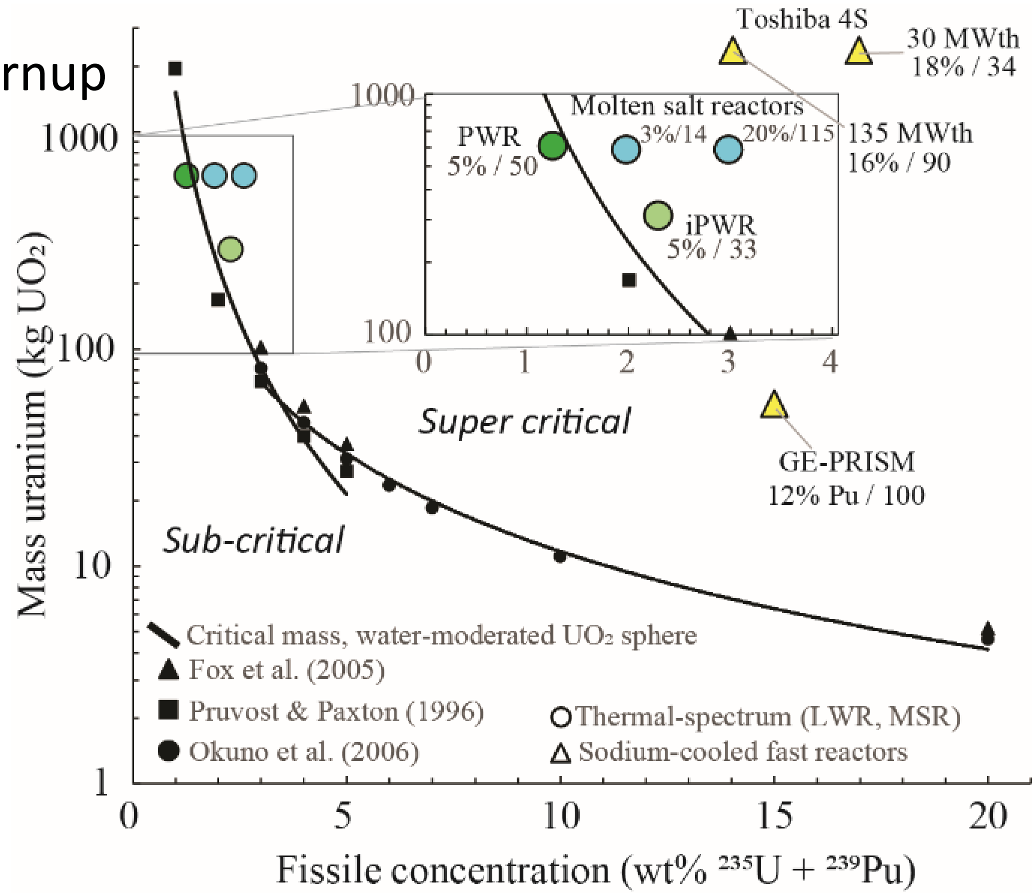
- Heat (storage duration, repository size): short-lived fission products
- Long-term **radiotoxicity** (^{239}Pu & ^{240}Pu) *versus* **dose** (long-lived FPs, ^{238}U daughters)
- Dose similar for low- & high-burnup fuels in geochemically reducing disposal environment
- Except for Yucca Mtn
  - Oxidizing geochemistry
  - Actinide mobility
  - Low burnup SMR fuel higher doses



Modified after Hedin (1997)

Re-criticality safety

- Neutron leakage & lower burnup → ^{235}U excess
- Water ingress (moderator)
- Fissile concentration, package geometry
- PWR limit: 5 wt% ^{235}U, >39 MWd/kg
- Exponential curve: < 1 fuel assembly / canister
  - Disassembly exposures
  - Large number of canisters



Conclusions

- o SCALE/ORIGEN (Origami)
  - For common reactors (*e.g.* LWRs)
  - Thermal-spectrum IMSR
- o Literature data for 4S (^{239}Pu-fueled)
- o Need more data for better accuracy
- o No benefit to SMR backend
  - Low burnup fuel
  - LILW volumes (moderator, reflectors, shielding)
  - Waste chemistry
  - Neutron leakage (broad applicability)
- Treatment, transportation, storage?