WASTE RADIOTOXICITY MINIMIZATION USING INNOVATIVE LWR-HTR-GCFR SYMBIOTIC FUEL CYCLES

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Worldwide Nuclear Waste Production

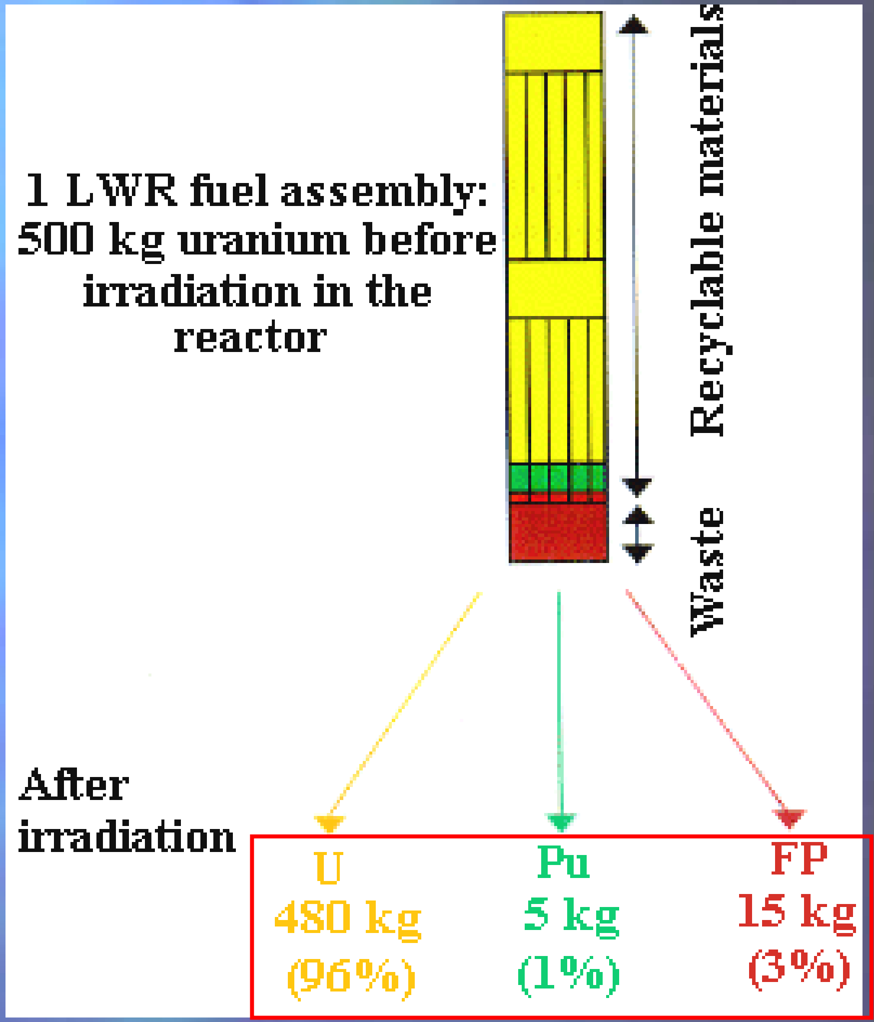
- More than 400 nuclear reactors producing over 16% of the world's electricity
- A Light Water Reactor with an output of 1000 MWe and an efficiency of 33% discharges annually 25 tons of nuclear waste
- In the fission process over 300 new species are formed (over 200 are radioactive and could pose an hazard)

Waste Burning Importance

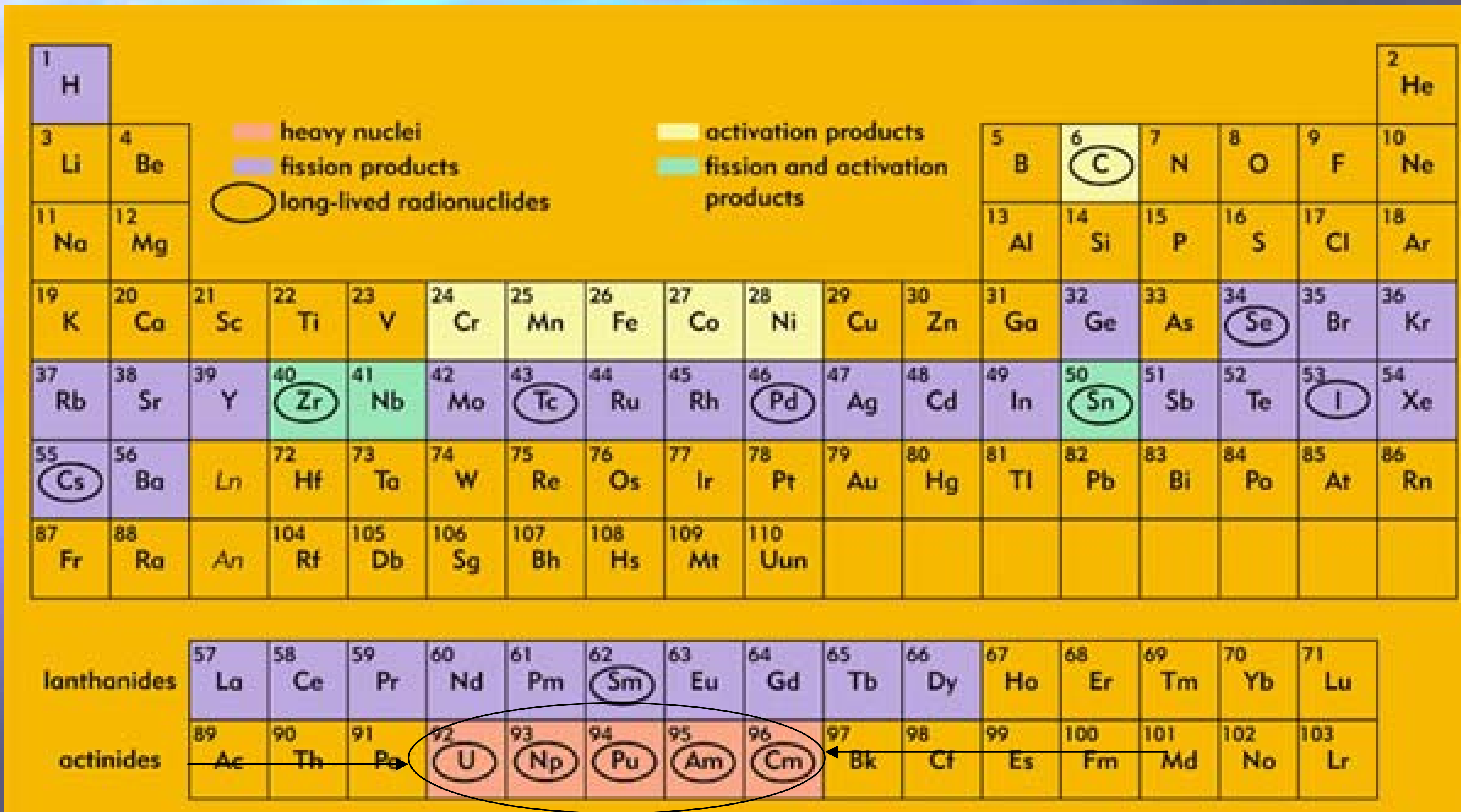
- Safe and economic permanent disposal of radioactive waste is assuming more and more importance
- Plutonium available (2000):
  - 500 t from reprocessing
  - 200 t from the dismantlement of nuclear weapons (START treaties)
  - 60-80 t/year from operating LWRs worldwide

Average Waste Composition

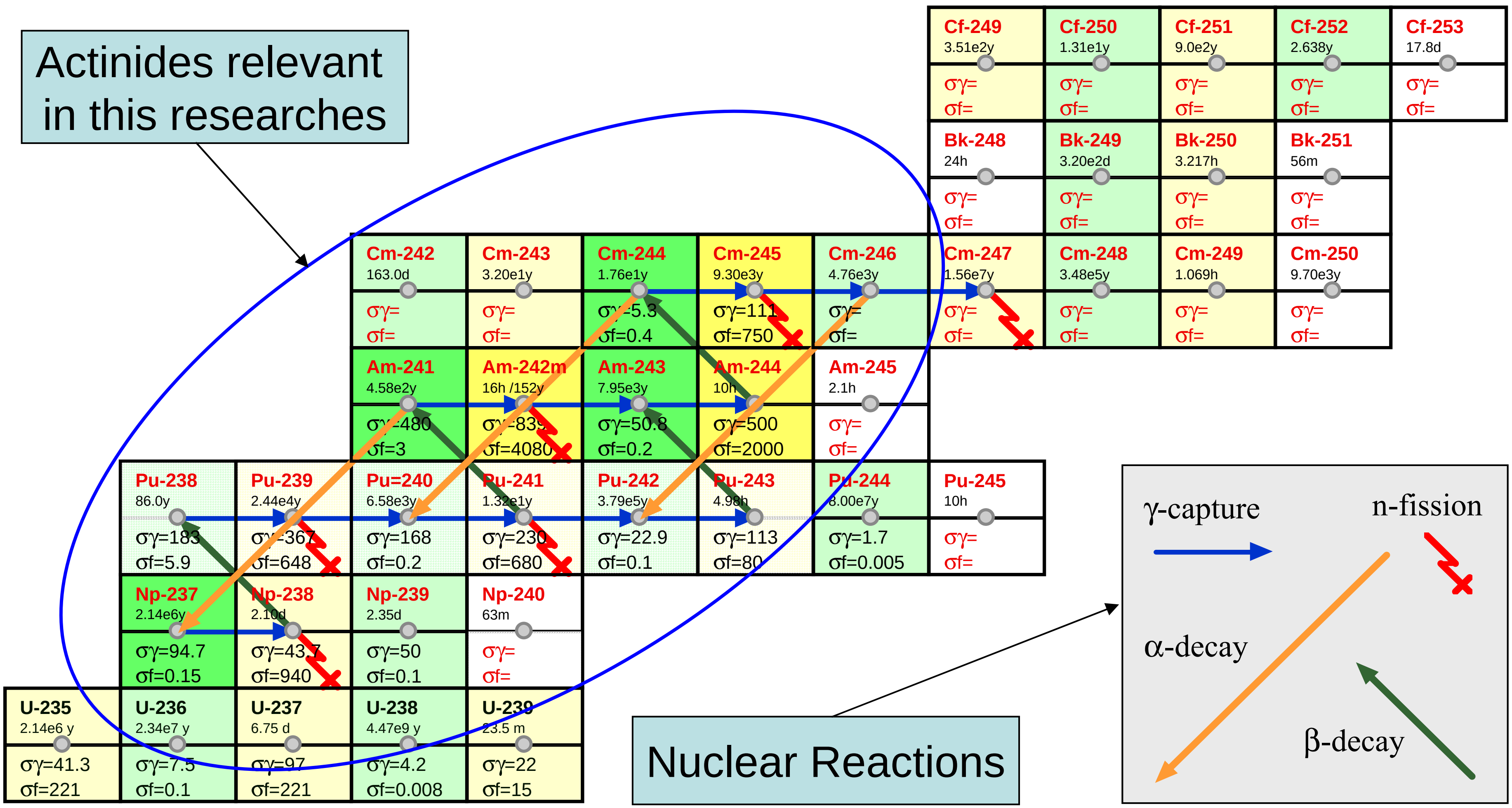
- After 3 years of permanence in the reactor core the fuel is transferred to cooling pools
- Its composition is:
  - 94% U238
  - 1% U235
  - 1% Pu
  - 0.1% MA (Np, Am, Cm)
  - 3-4% FP



Main elements present in Nuclear Waste

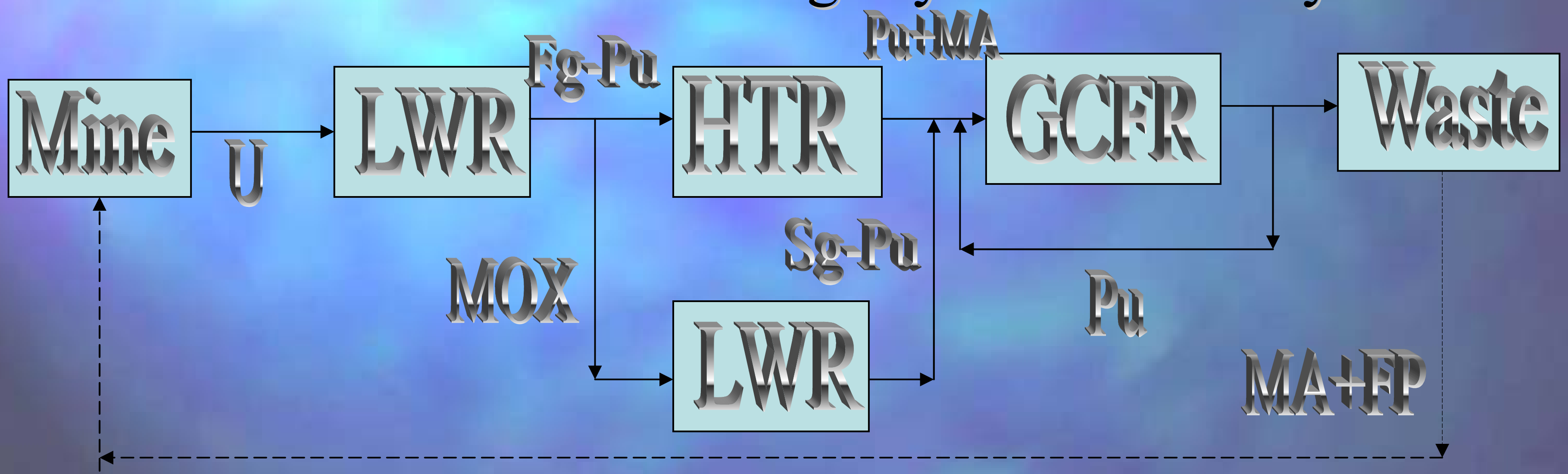


Actinides Chains

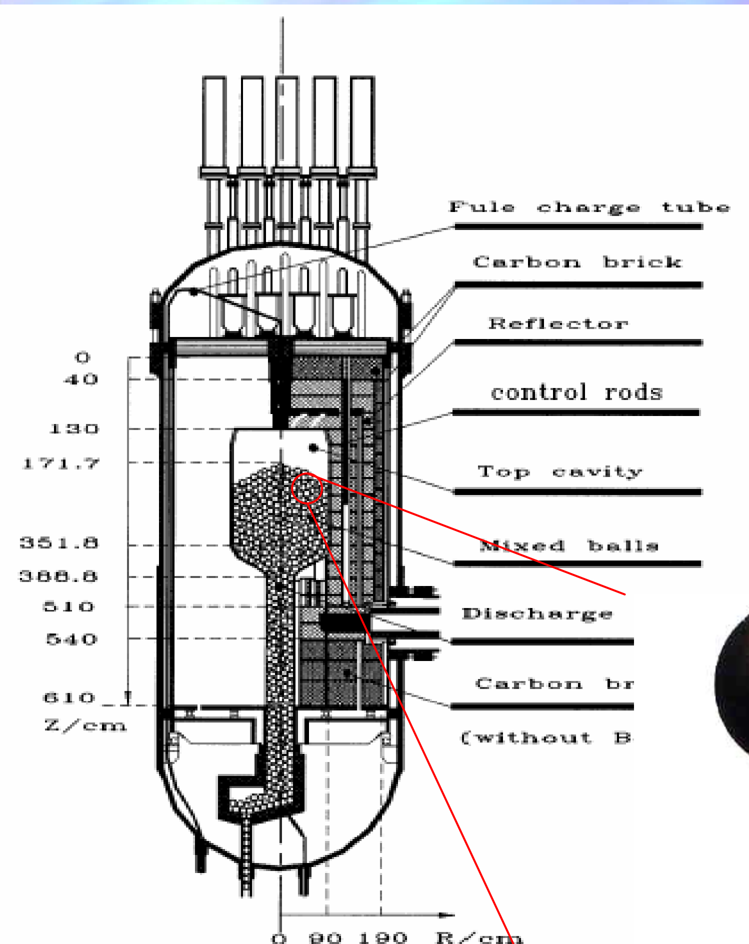


Symbiotic Fuel Cycles

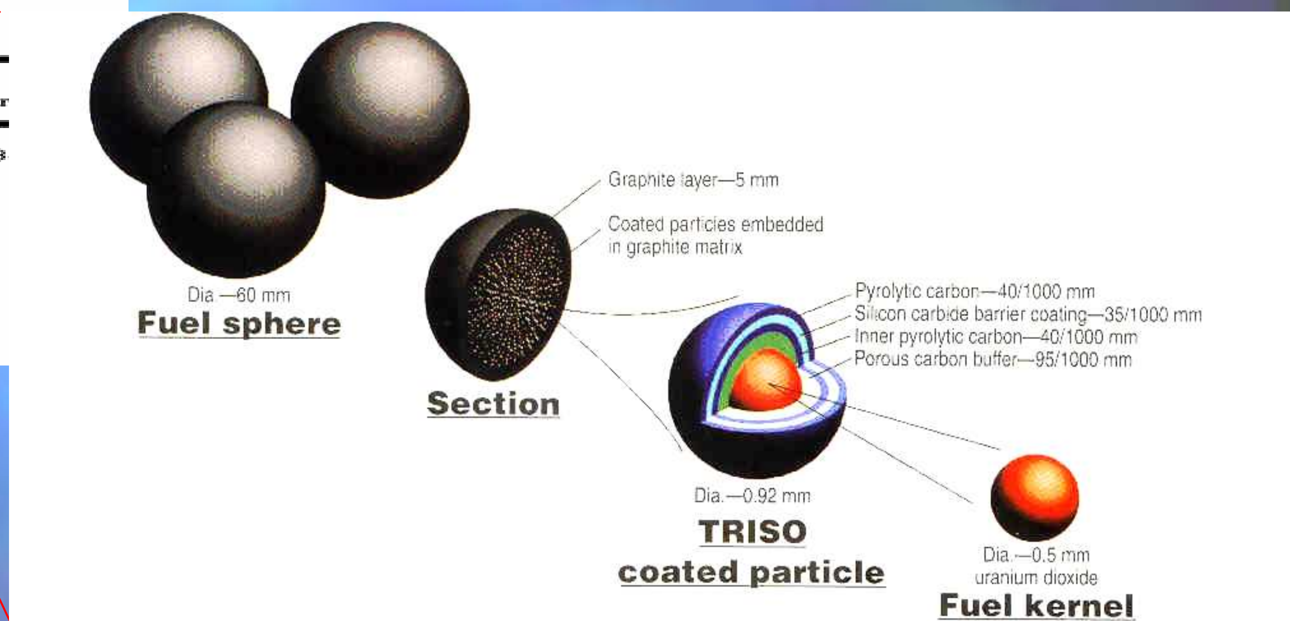
- By using a combination of LWR, HTR and GCFR:
  - The utilization of U resource could be enhanced
  - The waste radiotoxicity can be reduced by recycling of both Pu and the MA through symbiotic fuel cycles



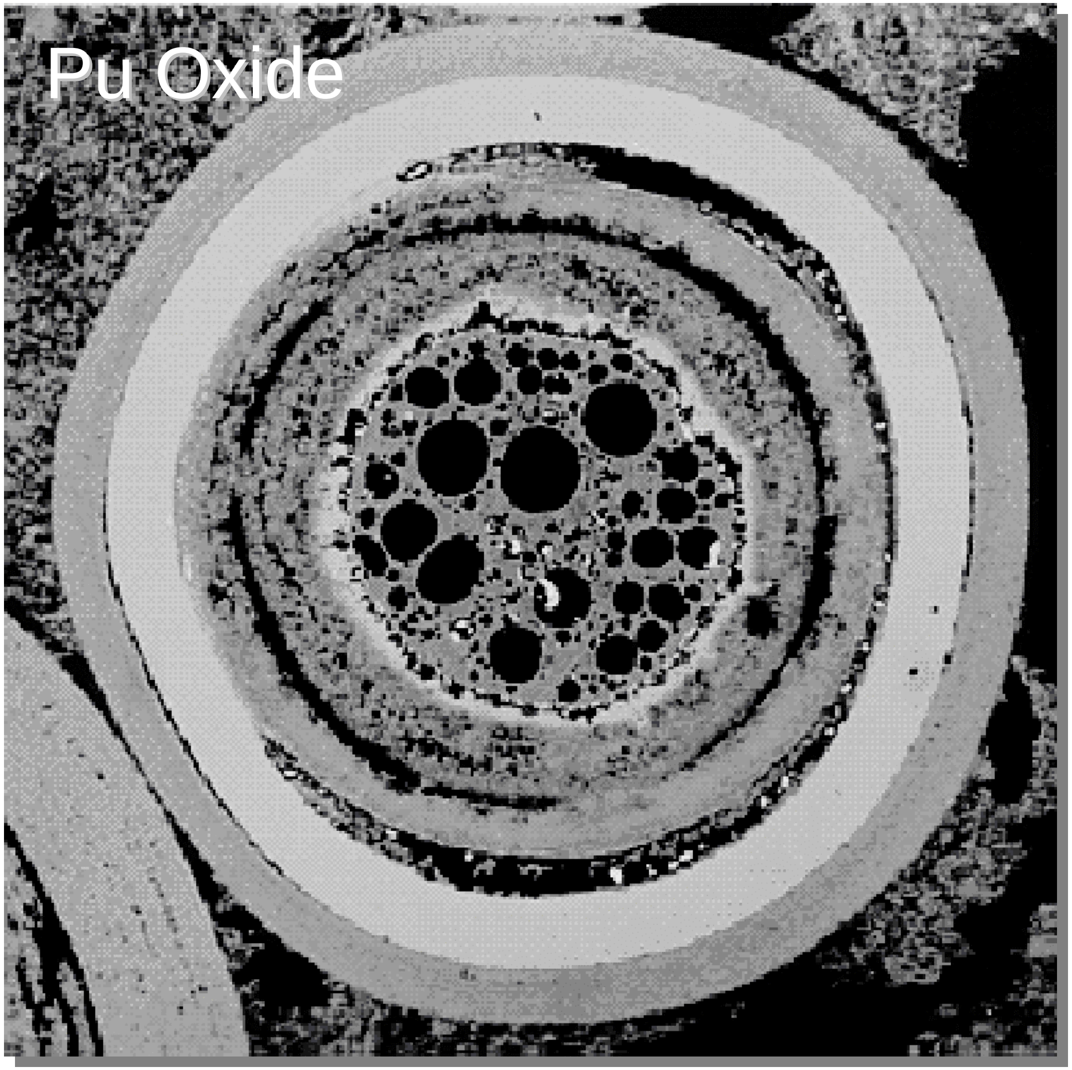
HTR - Pebble Bed



HTR-10 (CHINA):
A typical pebble-bed HTR



Coated Particle



747,000 MW-days/ton

Calculations Tools

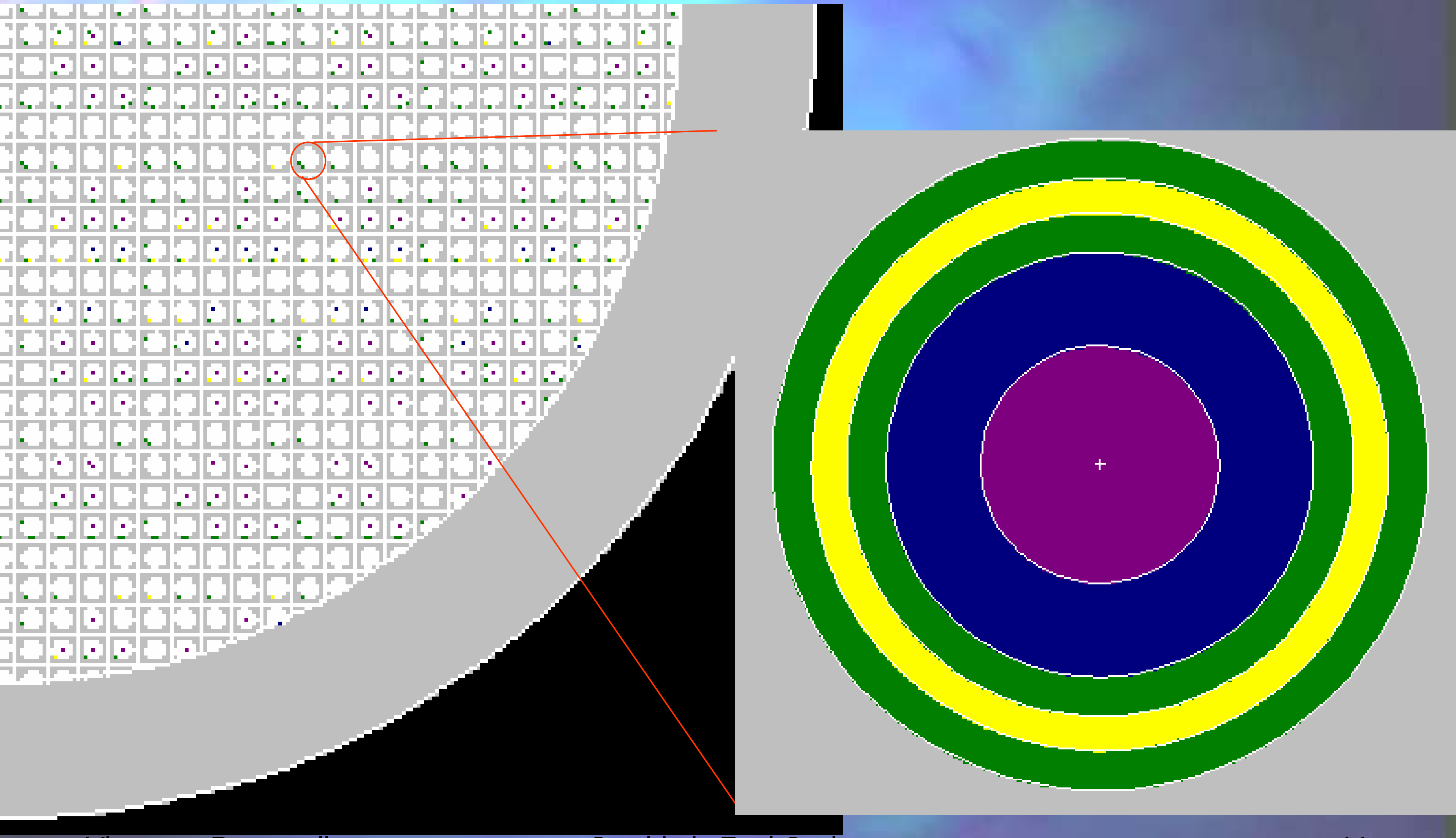
- MONTEBURNS neutronic code
- CARL2 code (*Bateman's equations based code*)

$$\begin{cases} dN_1 = -\lambda_1 N_1 dt \\ dN_2 = \lambda_1 N_1 dt - \lambda_2 N_2 dt \\ dN_3 = \lambda_2 N_2 dt - \lambda_3 N_3 dt \\ dN_4 = \lambda_3 N_3 dt - \lambda_4 N_4 dt \\ \dots \end{cases}$$

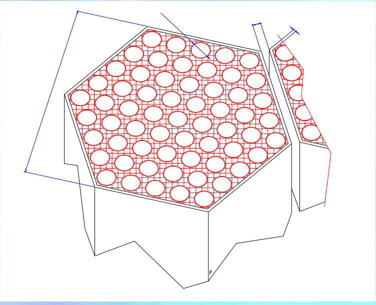
$$A_n = N_0 \cdot \sum_{i=1}^{n} c_i e^{-\lambda_i t} dt = N_0 \cdot (c_1 e^{-\lambda_1 t} + c_2 e^{-\lambda_2 t} + \cdots + c_n e^{-\lambda_n t})$$

$$c_m = \frac{\prod_{i=1}^{n} \lambda_i}{\prod_{i=1, i \neq m}^{n} (\lambda_i - \lambda_m)} = \frac{\lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdots \lambda_n}{(\lambda_1 - \lambda_m) \cdot (\lambda_2 - \lambda_m) \cdots (\lambda_n - \lambda_m)}$$

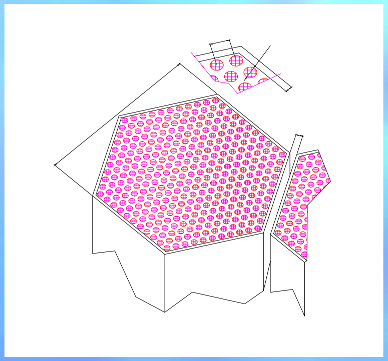
MCNP Input Model



Fuel elements for GCFR

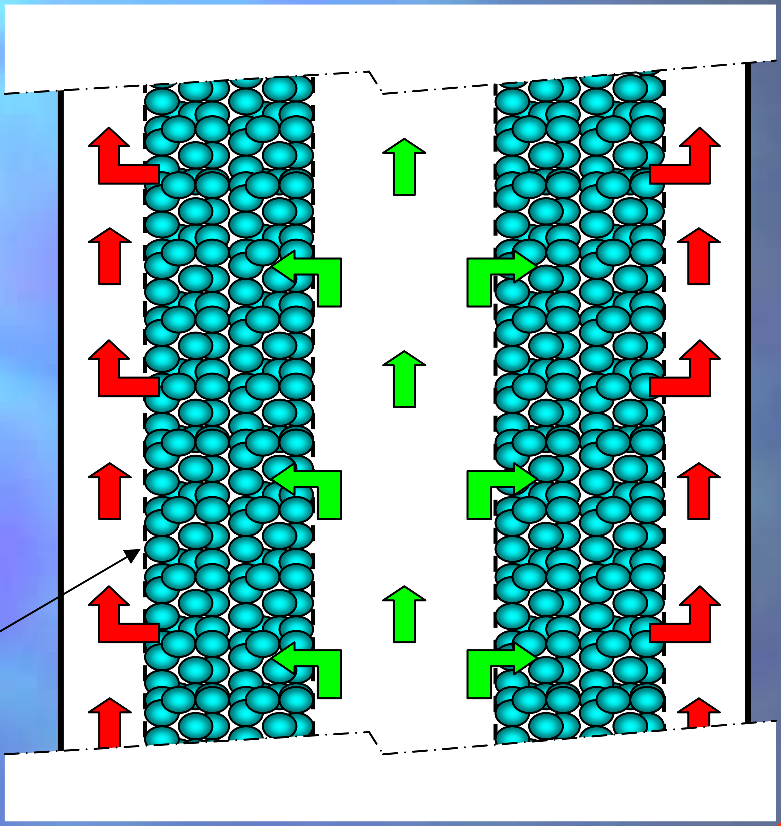


CERCER blocks



Pin Bundles

Analyzed Fuel Element

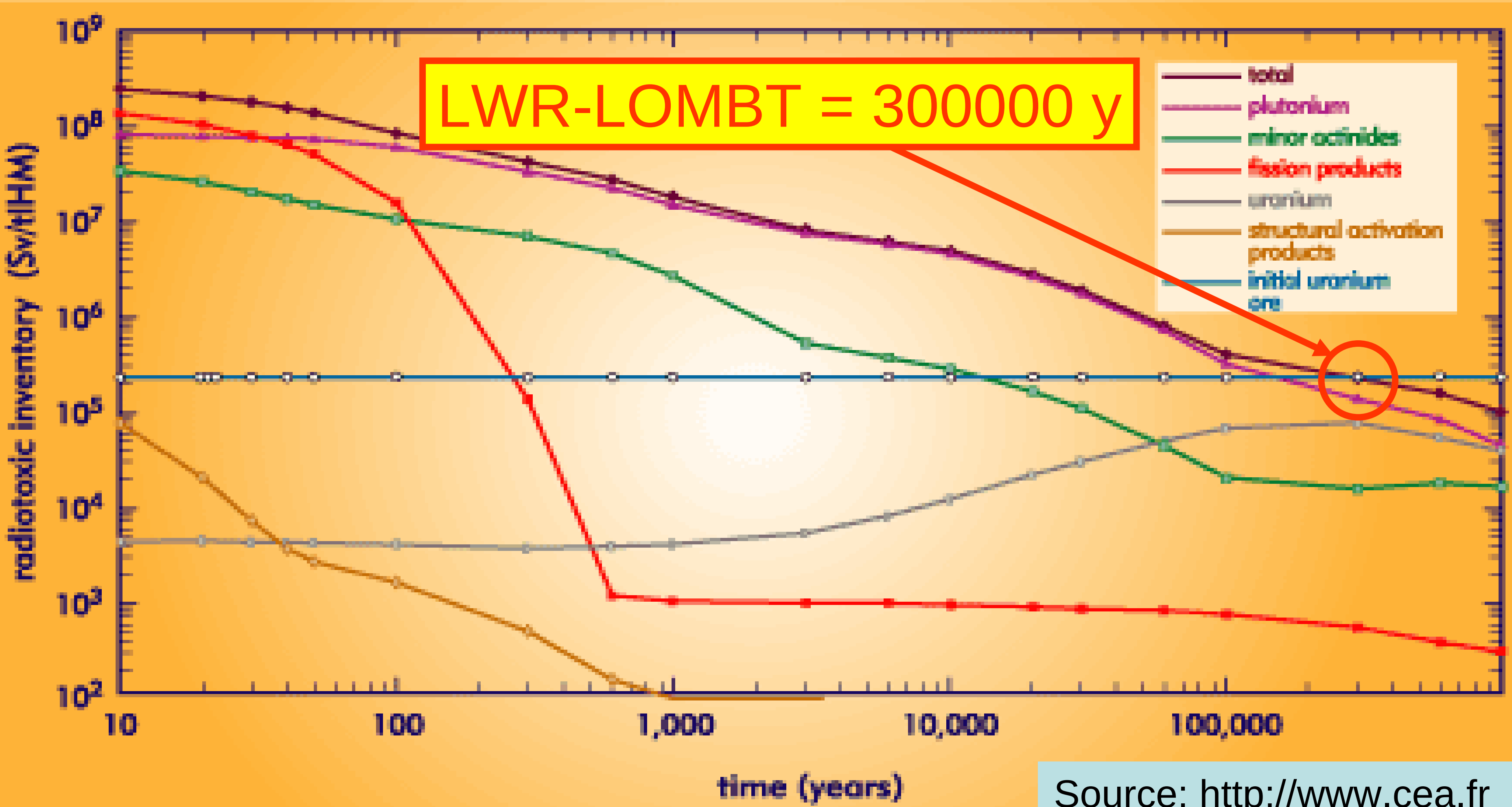


Coated Particle Bed

Reference Levels Evaluation

- In order to evaluate LOMBT (*Level Of Mine Balancing Time*) we need to state a reference level
- Now, the reference level for radiotoxicity of the natural U in mines (LOM) could be considered 20 Sv/Kg_{Unat}
- Great differences of U ore concentration in nature (e.g.: Cigar Lake, Canada: average 14%, but it is found as high as 55% in some places!)
- It is necessary to calculate a specific LOM referring to each different fuel composition

LWR Spent Fuel Radiotoxicity

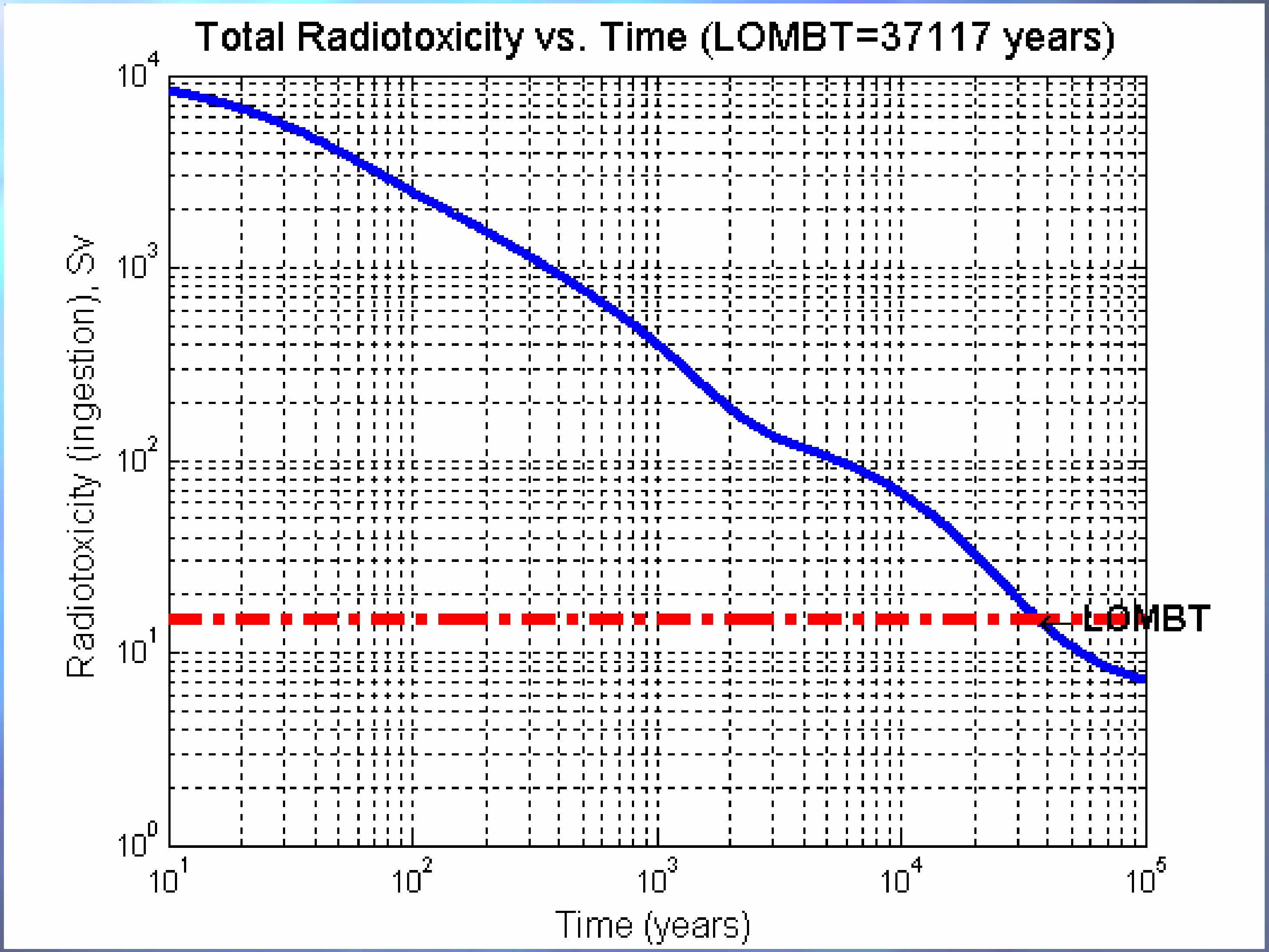


Source: http://www.cea.fr

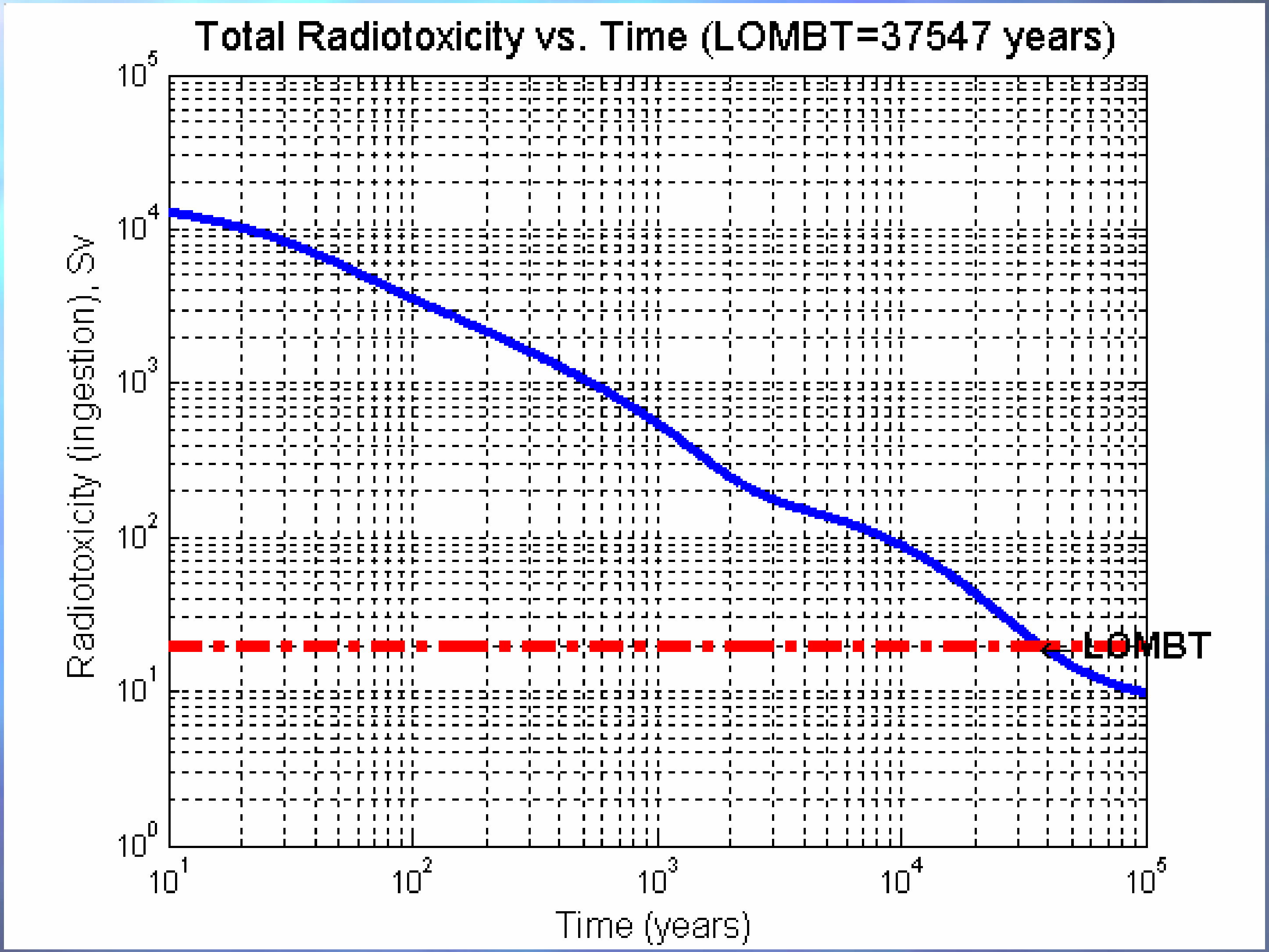
HTR loaded with Th-Pu

- We initially explored symbiotic fuel cycles coupling current LWRs with HTRs, in order to optimize Pu/Th ratios in the fuel
- So we analyzed First generation Pu (Pu^{Fg}):
  - $Th+Pu^{Fg}$ based fuel (ratio 3/1)
  - $Th+Pu^{Fg}$ based fuel (ratio 2/1)
  - $Th+Pu^{Fg}$ based fuel (ratio 1/1)

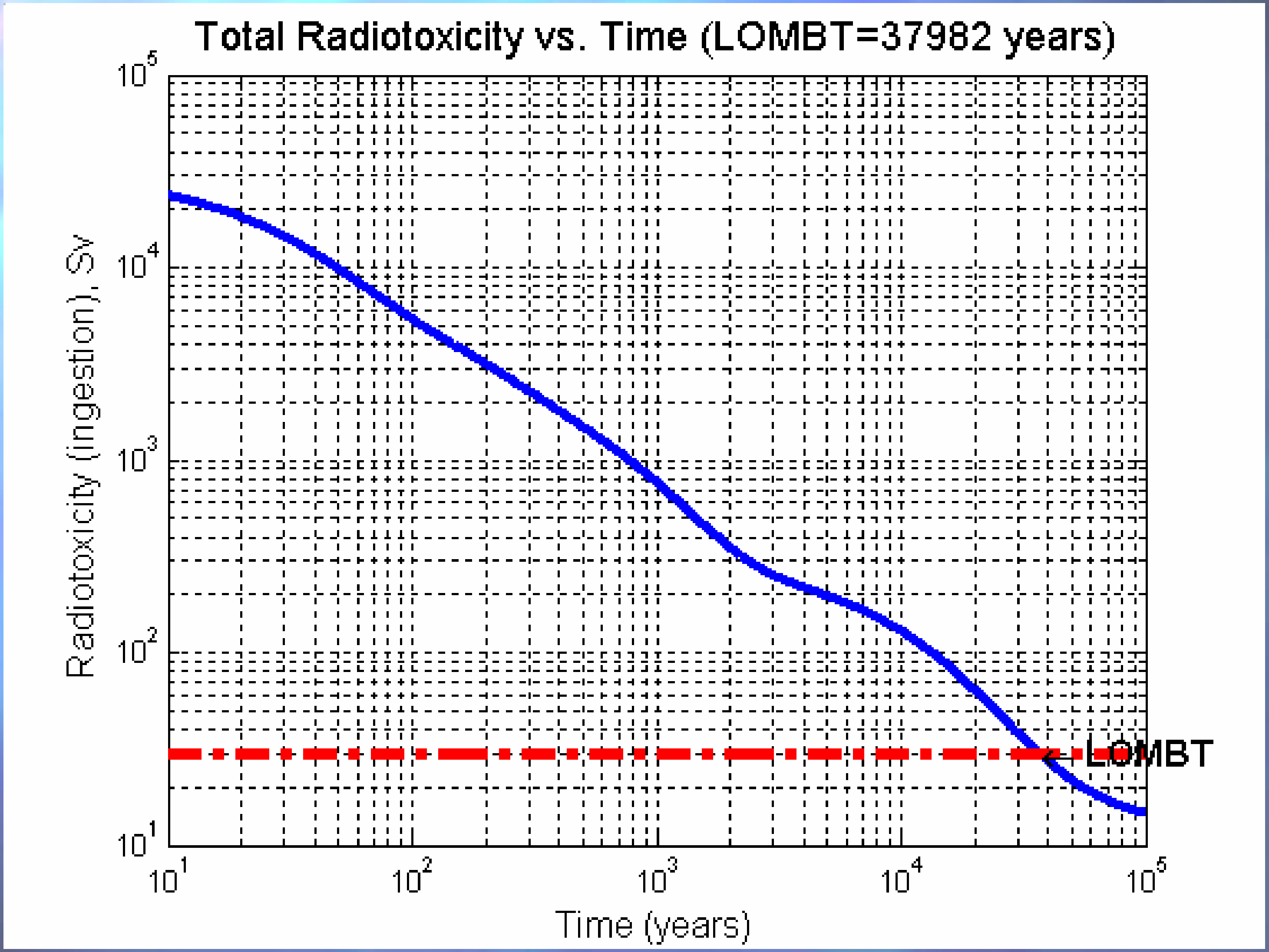
HTR loaded with Th-Pu(3/1)



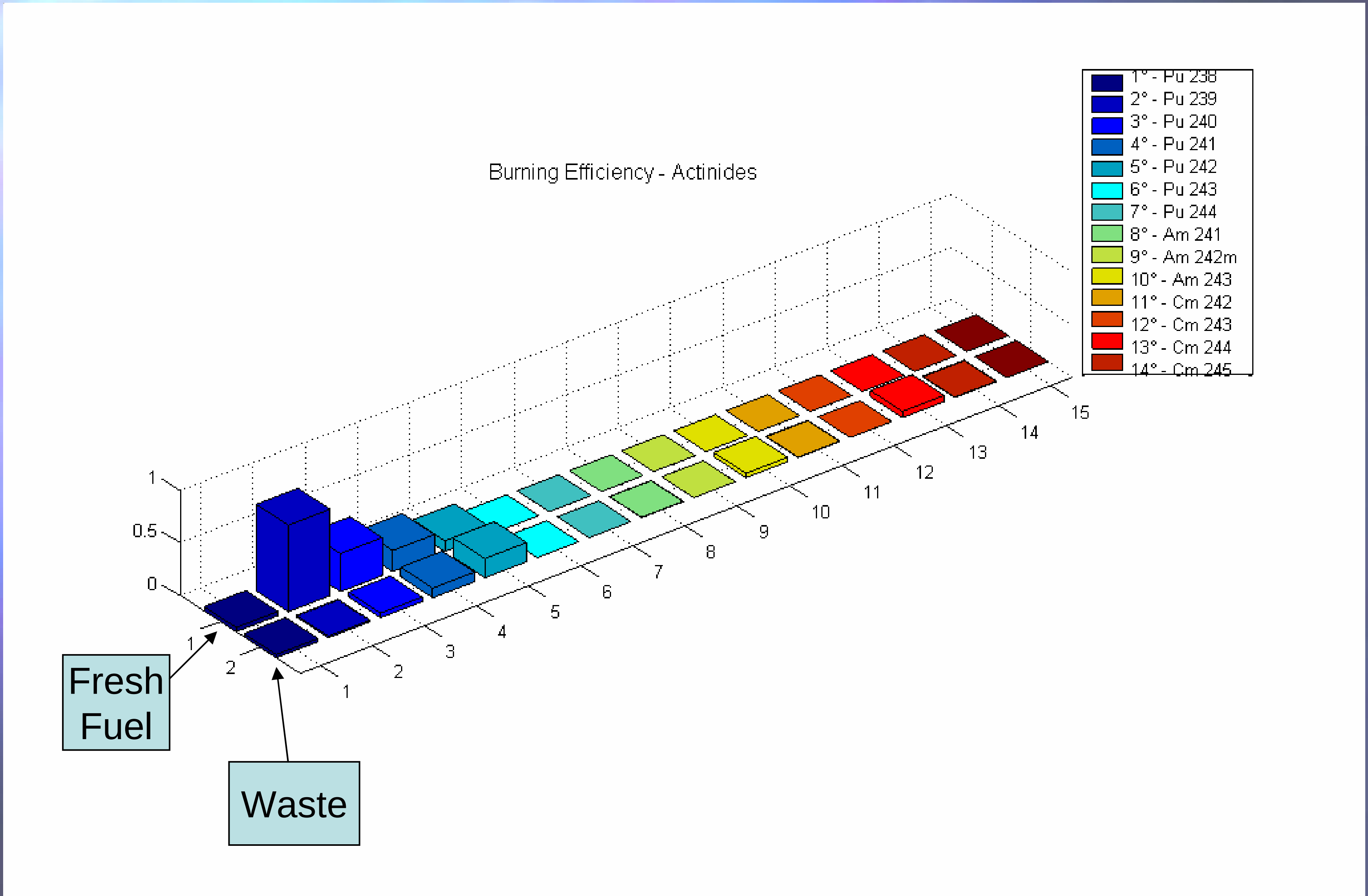
HTR loaded with Th-Pu(2/1)



HTR loaded with Th-Pu(1/1)



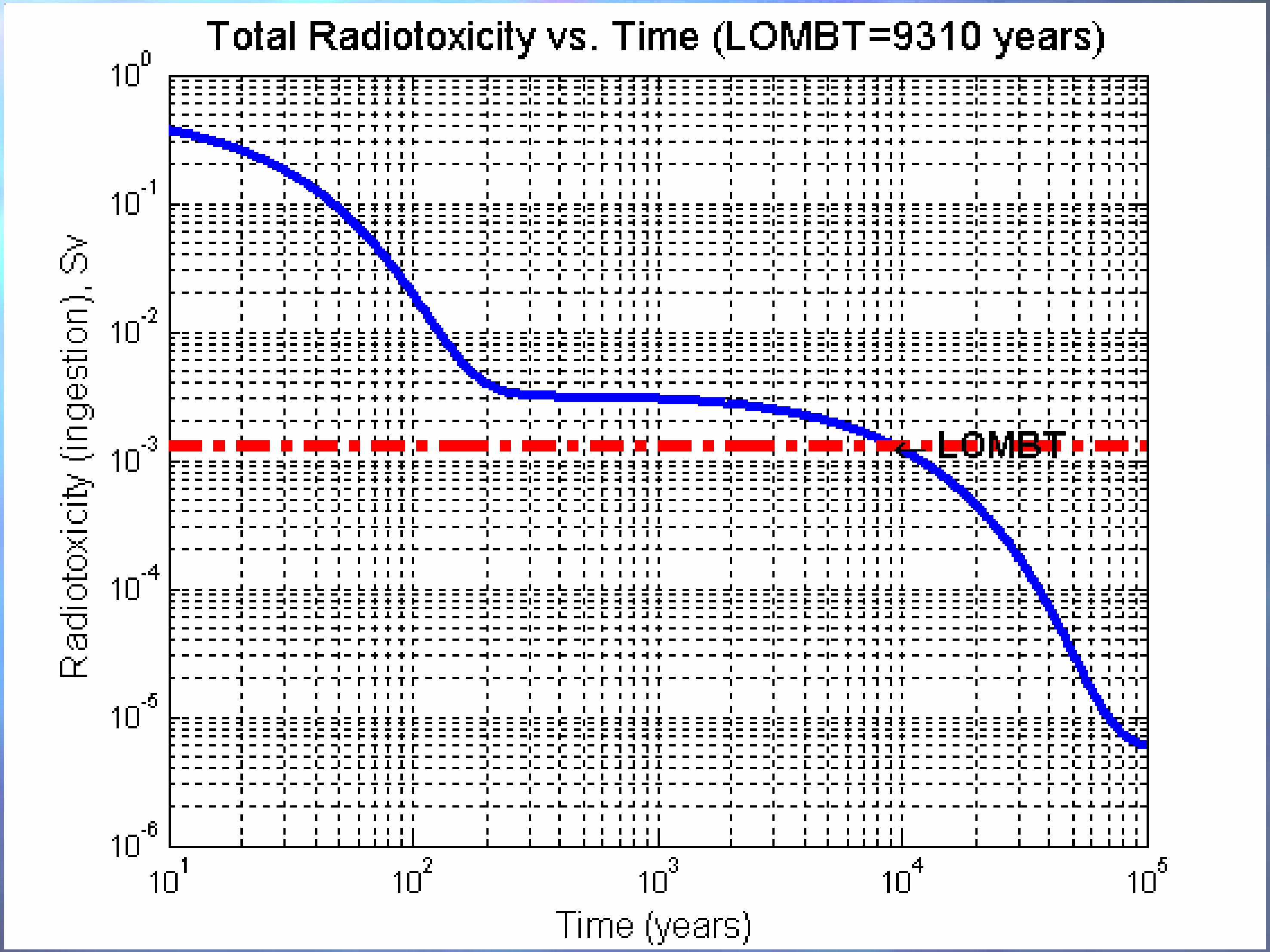
Actinides in HTR (Th/Pu 1/1)



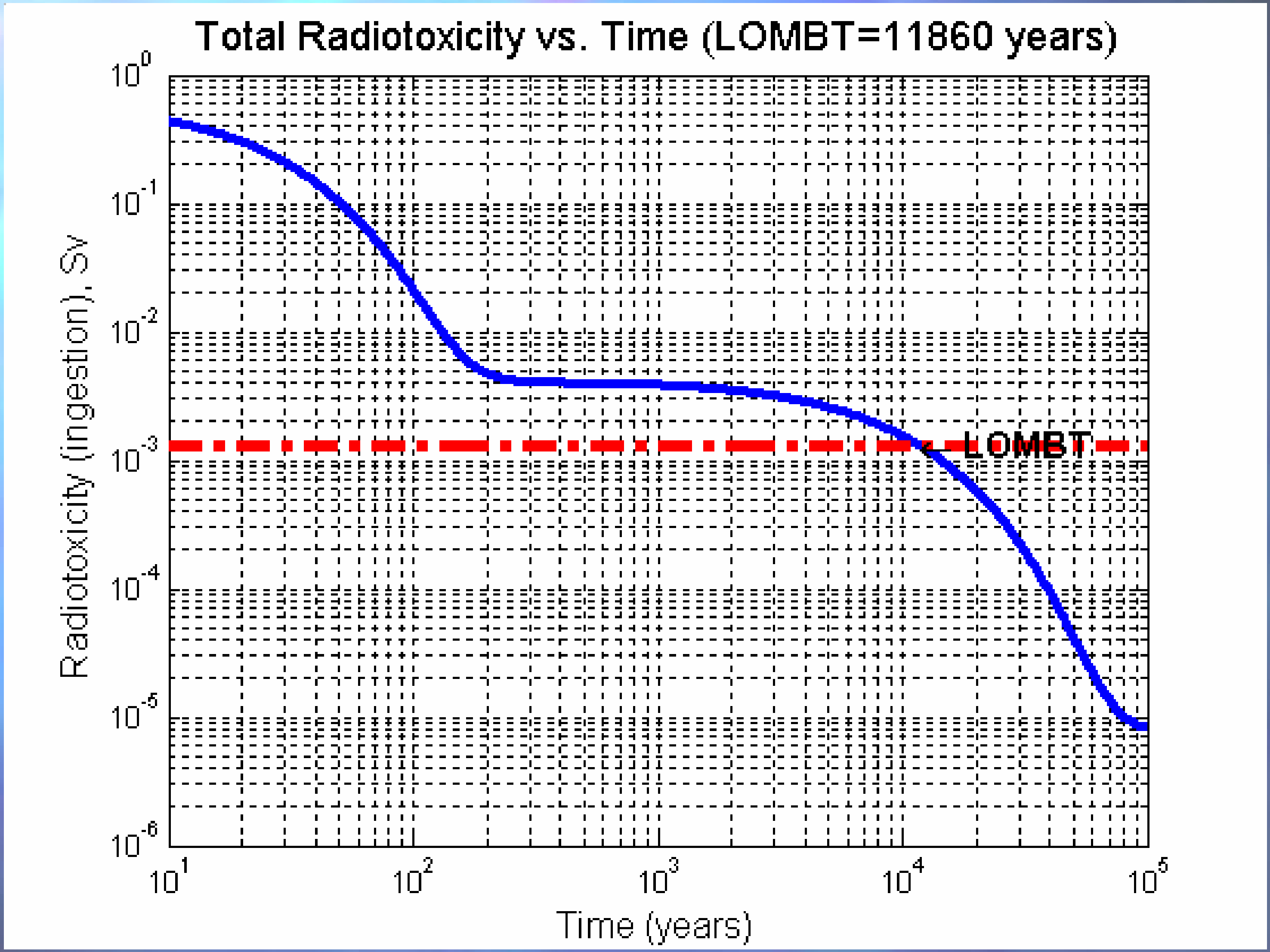
GCFR loaded with U-Pu-MA

- Starting from the results on HTR, to close the cycle, we used GCFRs to burn MA (which are important contributors to long term waste radiotoxic inventory)
- So we analyzed:
  - Pu^{Sg} + MA + Pu deriving from HTR loaded with Pu^{Sg} in a U^{238} matrix (ratio Pu/MA/U238 10/1/40)
  - Pu^{Sg} + MA + Pu deriving from HTR loaded with Pu^{Sg} in a U^{238} matrix (ratio Pu/MA/U238 10/1/40)
  - Pu^{Fg} + MA + Pu deriving from HTR loaded with Pu^{Fg} in a U^{238} matrix – increased moderation (ratio Pu/MA/U238 10/1/40)

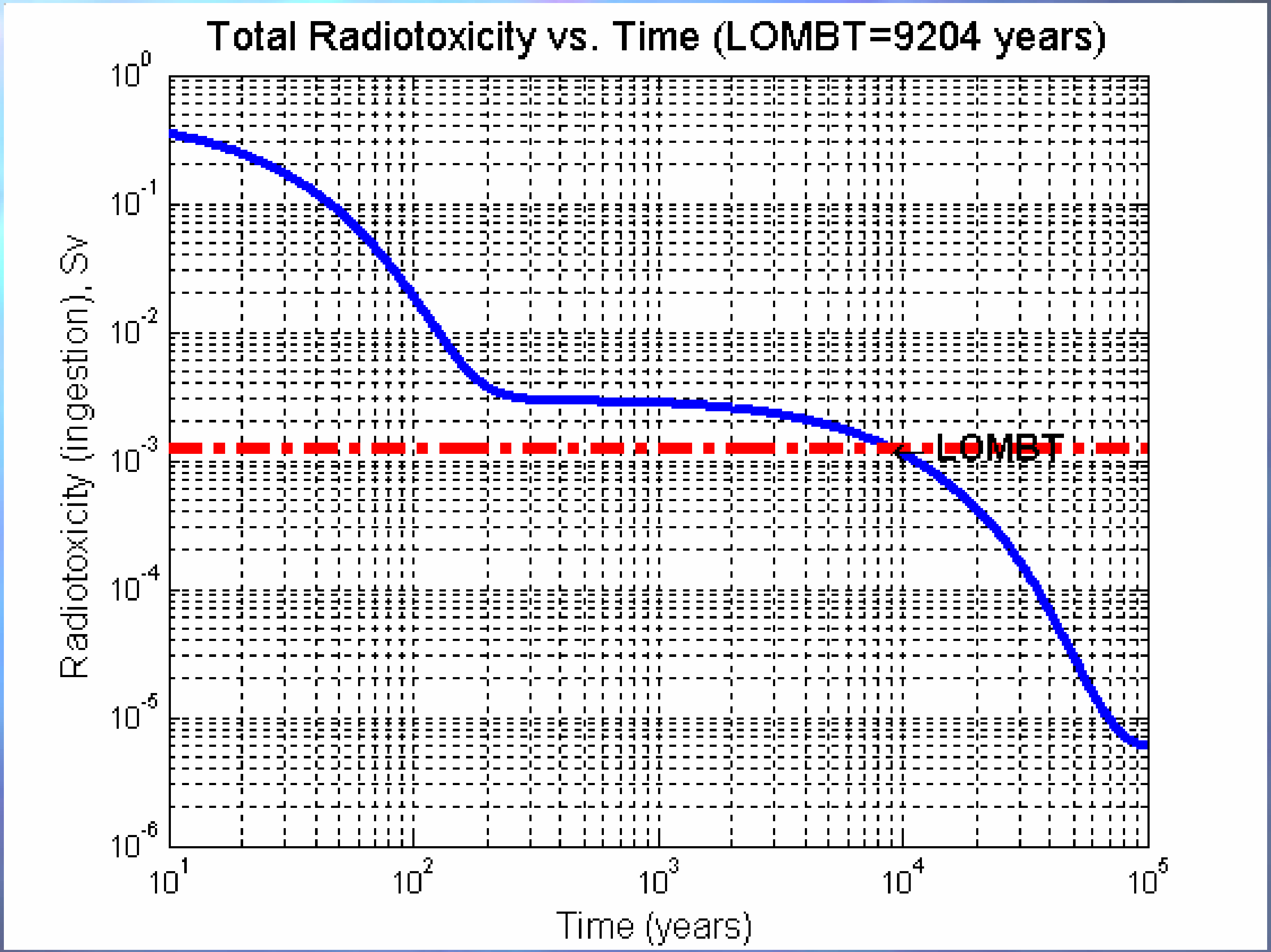
GCFR loaded with Pu^{Sg}+U+MA(10/40/1)



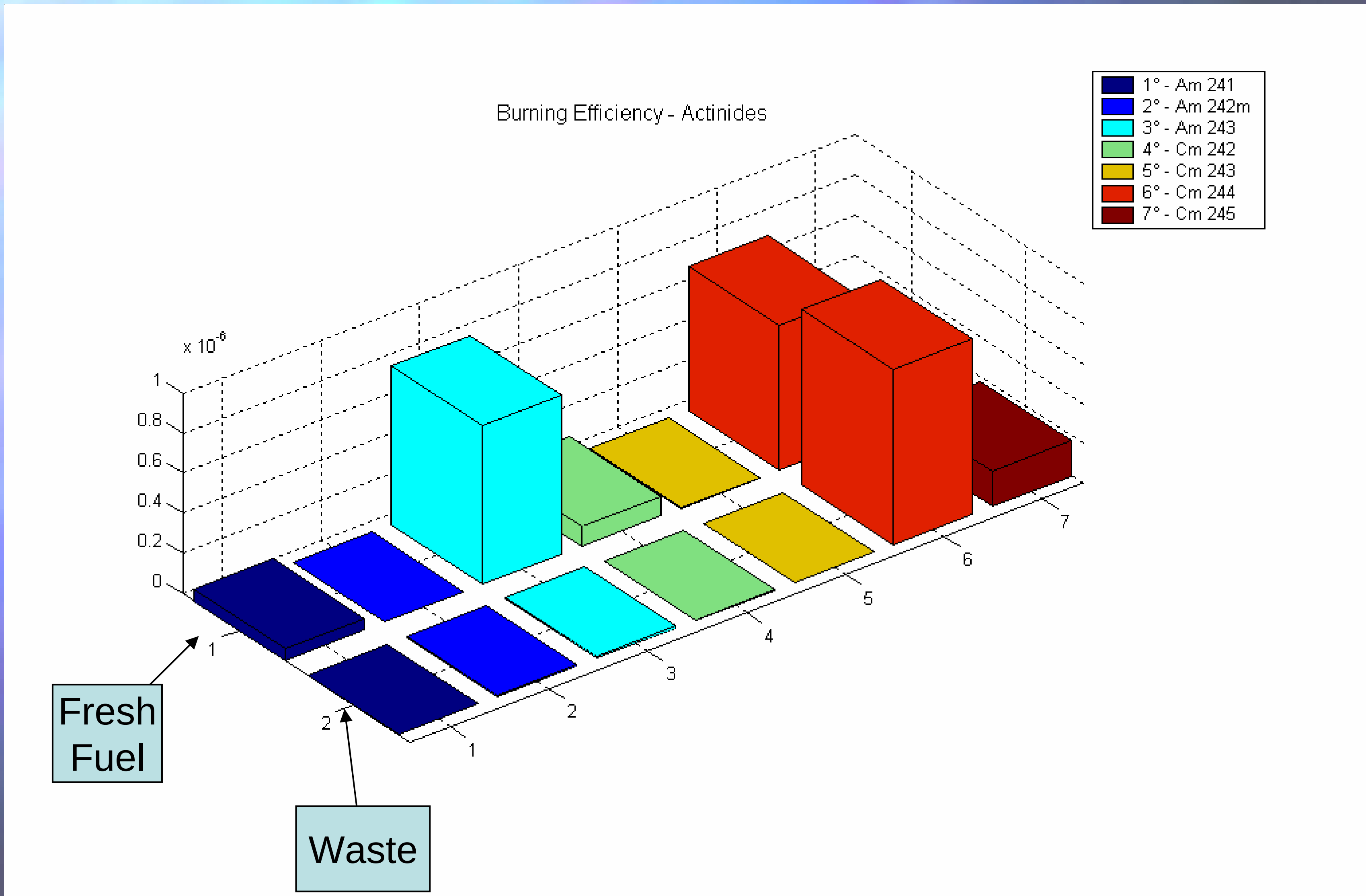
GCFR [Pu^{Sg}+U+MA(10/40/1) CP_{mod}]



GCFR loaded with Pu^{Fg}+U+MA(10/40/1)



MA in GCFR (Pu^{Fg})



Summary of Obtained Results

Case	Reactor	Fuel	LOMBT [y]	$\frac{\text{Energy}}{g_{Pu}}$	$\frac{Pu_{out}}{Pu_{in}}$	$\frac{TRU_{out}}{TRU_{in}}$	$\frac{Act_{out}}{Act_{in}}$
a	HTR	Pu^{Fg}/Th (1/1)	37982	60.16 GJ	24.14%	31.75%	63.88%
b	HTR	Pu^{Fg}/Th (1/2)	37547	59.40 GJ	27.75%	33.88%	76.25%
c	HTR	Pu^{Fg}/Th (1/3)	37117	58.89 GJ	29.06%	34.37%	81.94%
d	GCFR	$Pu^{Fg}/MA/U^{238}$ (10/1/40)	9204	154.44 GJ	85.66%	86.77%	57.78%
e	GCFR	$Pu^{Sg}/MA/U^{238}$ (10/1/40)	9310	155.26 GJ	85.85%	87.77%	57.57%
f	$GCFR^{mod}$	$Pu^{Sg}/MA/U^{238}$ (10/1/40)	11860	105.57 GJ	98.02%	98.95%	70.64%

Conclusions [1/2]

- Using HTRs, we can burn Pu and reduce significantly the radiotoxic inventory ***producing and not consuming energy***
- The LOMBTs depend on the compositions of both the spent and the fresh fuel
- If we use ultra high burnup, the long term radiotoxicity arises mainly from the presence of Cm^{244} in the spent fuel (a single nuclide and not a mix)

Conclusions [2/2]

- An accurate choice of LWR – HTR – GCFR integrated fuel cycles could be an important step on the way to solving the spent fuel problem
- Even if we have performed a lot of calculations, the research is still in a preliminary stage
- Therefore it is very important to continue these researches in order to solve these still open questions for a wider use of nuclear energy