WASTE RADIONUCLIDE 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

Actinides relevant in this researches

Nuclear Reactions

γ-capture → n-fission
α-decay → β-decay
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

Pu Oxide

747,000 MW-days/ton
Calculations Tools

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

\[
\begin{align*}
\frac{dN_1}{dt} &= -\lambda_1 N_1 \\
\frac{dN_2}{dt} &= \lambda_1 N_1 - \lambda_2 N_2 \\
\frac{dN_3}{dt} &= \lambda_2 N_2 - \lambda_3 N_3 \\
\frac{dN_4}{dt} &= \lambda_3 N_3 - \lambda_4 N_4 \\
& \vdots
\end{align*}
\]

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

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

LWR-LOMBT = 300000 y

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)
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:
  – $\text{Pu}^{\text{Sg}} + \text{MA} + \text{Pu}$ deriving from HTR loaded with $\text{Pu}^{\text{Sg}}$ in a $\text{U}^{238}$ matrix (ratio $\text{Pu}/\text{MA}/\text{U}^{238}$ 10/1/40)
  – $\text{Pu}^{\text{Sg}} + \text{MA} + \text{Pu}$ deriving from HTR loaded with $\text{Pu}^{\text{Sg}}$ in a $\text{U}^{238}$ matrix (ratio $\text{Pu}/\text{MA}/\text{U}^{238}$ 10/1/40)
  – $\text{Pu}^{\text{Fg}} + \text{MA} + \text{Pu}$ deriving from HTR loaded with $\text{Pu}^{\text{Fg}}$ in a $\text{U}^{238}$ matrix – increased moderation (ratio $\text{Pu}/\text{MA}/\text{U}^{238}$ 10/1/40)
GCFR loaded with Pu$^{Sg}$+U+MA(10/40/1)
GCFR \([\text{Pu}^{Sg}+\text{U}+\text{MA}(10/40/1) \ CP_{mod}]\)
GCFR loaded with Pu^{Fg} + U + MA(10/40/1)
## Summary of Obtained Results

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