Isotopic Analysis of the In-Zinerator Actinide Management System

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Overview

- In-Zinerator
- Problem Description
- Isotopic Inventory Tool – MCise
- Results
- Future Work
In-Zinerator

- Designed to reduce heat load, and radiotoxicity of nuclear waste from LWR
In-Zinerator - Features

• Sub-critical blanket with Z-pinch fusion
  – Fusion Source – 200 MJ D-T, 0.1 Hz
• Fuel - Actinides in eutectic liquid form
  – (LiF)$_2$AnF$_3$
  – Continuously reprocessed
• Coolant – Lead surrounding an annular of 5-cm fuel tubes
• Structural Material – Hastelloy-N
In-Zinerator - Challenges

• Fusion yield of Z-pincho
• Reactivity control
• Shock mitigation from x-ray pulses
• Heat Removal
• Safety and concerns from liquid fuel
• Tritium breeding
• Burnup and transmutation calculation
What is MCise?

- Monte Carlo Isotopic Simulation Engine

- Important Capabilities
  - Online extraction – FP removal
  - Continuous feed – Fuel replenishment
Background & Motivation

Control Volume
Neutron Flux ($\Phi$), Residence Time ($t_R$)

\[ \lambda_{\text{eff}} \equiv \int \phi(E)\sigma(E)dE + \lambda_{\text{decay}} \]

Mean reaction time
\[ t_m = \frac{1}{\lambda_{\text{eff}}} \]

- Convert residence time to number of mean reaction times for this isotope
\[ n_R = \frac{t_R}{t_m} \]

- Randomly sample number of mean reaction times before next reaction
\[ n = -\ln \xi \]
Background & Motivation

Control Volume
Neutron Flux (Φ), Residence Time (t_R)

\[ n \cdot t_m \quad t_R - n \cdot t_m \]

\[ \lambda_{eff} = \int \phi(E)\sigma(E)dE + \lambda_{decay} \]

Mean reaction time:
\[ t_m = \frac{1}{\lambda_{eff}} \]

• While \( n_R > n \), reaction occurs.
  - Randomly sample a type of reactions
  - \( t_R \rightarrow t_R - n \cdot t_m \)
  - Repeat until \( n > n_R \)
  • Particle leaves control volume (history ends?)
<table>
<thead>
<tr>
<th>Element</th>
<th>Transport</th>
<th>Inventory Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source quanta</td>
<td>Neutral particles</td>
<td>Individual atoms</td>
</tr>
<tr>
<td>Characteristic dimension</td>
<td>Length of geometric cell</td>
<td>Residence time in control volume</td>
</tr>
<tr>
<td>Basic sampling quanta</td>
<td>Mean free paths between reactions (macroscopic cross-section)</td>
<td>Mean times between reactions (effective total transmutation &amp; decay rate)</td>
</tr>
<tr>
<td>Primary particle characteristic</td>
<td>Energy</td>
<td>Isotopic identity</td>
</tr>
</tbody>
</table>
• Flux obtained from MCNP
• $t_R = 100$ days, $T_{sim} = 20000$ days
• Two sources
  – Initial core loading - uniformly distributed in the core
  – Continuous feed - at the beginning of the core
Birth Time of Atom Sources

- Initial Core Loading – $t_{sim} = 0$
- Continuous feed
  - Feed rate at anytime must be equal to half of FP removal rate ($dF/dt$)
- Assume constant power level,

$$\dot{F} = \kappa P - \frac{\varepsilon \dot{C}}{I} F, \quad F(0) = 0$$

- $F$ = a total amount of FP [atoms]
- $P$ = a desired power level [energy/time]
- $\kappa$ = a number of FP released for energy released [atoms/energy]
- $\varepsilon$ = FP separation efficiency
- $I$ = a total initial inventory [atoms]
- $\dot{C}$ = a processing capacity [atoms/time]
Inventory of FP at any time is given by

\[ F(t) = \frac{\kappa PI}{\varepsilon C} (1 - e^{-\varepsilon \dot{C} t / I}) \]

Feed Rate is therefore given by

\[ \frac{1}{2} \frac{\varepsilon \dot{C}}{I} F(t_{\text{sim}}) = \frac{\kappa P}{2} (1 - e^{-\varepsilon \dot{C} t_{\text{sim}} / I}), \quad 0 < t_{\text{sim}} < T_{\text{sim}} \]
Results

- Equilibrium achieved after ~ 30 years
Results

Criticality

![Graph showing criticality over operation time]

- TRU feed
- TRU and Li-6 Feed

Criticality values over operation time.

Operation Time (days)

<table>
<thead>
<tr>
<th>Keff</th>
<th>Operation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.955</td>
<td>0</td>
</tr>
<tr>
<td>0.96</td>
<td>500</td>
</tr>
<tr>
<td>0.965</td>
<td>1000</td>
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<tr>
<td>0.97</td>
<td>1500</td>
</tr>
<tr>
<td>0.975</td>
<td>2000</td>
</tr>
</tbody>
</table>
Results

Energy Multiplication

Operation Time (days)

Energy Multiplication

- TRU Feed
- TRU and Li-6 Feed
Results

Tritium Breeding Ratio

![Graph showing Tritium Breeding Ratio vs Operation Time (days)].

- **TRU Feed**
- **TRU and Li-6 Feed**
• Actinides burnup = 1335 kg/years
Future Work

• Need a tighter coupling between neutronics and isotopics
  – Imply reactivity control mechanism

• Iterative scheme between MCNP & MCise
  1. Use MCNP to find the reactivity control state, \( S_i \), that achieves a desired energy multiplication for the current isotopic inventory state, \( I_i \).
  2. Use the neutron flux from step 1 with MCise to determine isotopic distributions for the next time step, \( I_{i+1} \).
Question & Comments

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