Kinetic Analysis of Coupled Pulse Reactor for NPL Experiment

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Background

Nuclear-Pumped Laser; One of Direct Nuclear Energy Conversions

Nuclear Energy
- FP kinetic energy

Direct Conversion

Optical Energy
- Laser

Optical Applications, Photonics Society

Nuclear Reactor for Nuclear-Pumped Laser designed by IPPE, Russia

Weakly Coupled System
(Decoupled Spectrum System)
- Pulse Cores (Fast Spectrum)
- Subcritical Laser-Cell Assembly (Thermal Spectrum)

Fast neutrons pulsed from pulse cores
Diffusion and thermalization of the fast neutrons in the assembly
U235 fissions on the fuel-coated wall + Nuclear-pumping of laser medium

Front view
- Pulse core with high-enriched uranium
- High-enriched metallic uranium coating

Side view
- Pulse cores (Fast Spectrum)
- Subcritical Laser-Cell Assembly (Thermal Spectrum)

Laser-Cell
- Highly enriched metallic uranium coating (~5 micron)
- Stainless steel tube
- Ar : Xe = 200 : 1

Laser-Cell
- Pulse core with high-enriched uranium
- High-enriched metallic uranium coating

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Nuclear Pumped Laser Experiment Reactor in IPPE

1. Fast pulse cores
2. Laser cell assembly
3. Inner polyethylene moderator
4. Outer polyethylene moderator
5. Laser cells

1. Moveable core
2. Core
3. Core
4. Reactivity control system
5. U-Mo alloy core
6. Core cover
7. B10+moderator
8. Support tube
9. Transient rod
10. Reactivity control rod
11. Safety rod

BARS-6 pulse reactor
Purpose of study

- To show the possibility of performing NPL experiments using the pulse reactor concept with low-enriched uranium by performing kinetic analysis of the prompt supercritical condition.
Methodology

Space-Dependent Kinetic Model

Integral Kinetic Model + Monte Carlo Method

\[ N_i(t) = \sum_{j=1}^{n} \int_{-\infty}^{t} \alpha_{ij}(t - t') N_j(t') dt' \]

Fission Probability Density Function

Secondary fission density in region i provided by the first fission in region j with time deference t-t'.

Fission Density at region i [fissions@i/sec]

\[ \alpha_{ij} \] calculation method has developed using Monte Carlo method by the modified MVP2.0.
Outline of $\alpha_{ij}$ calculation method

- Introduction of $C_{ij}$

$$N_i(t) = \sum_{j=1}^{n} \int_{-\infty}^{t} \alpha_{ij}(t - t') N_j(t') dt'$$

$$C_{ij}(\tau) \equiv \int_{0}^{\tau} \alpha_{ij}(\tau') d\tau' \quad \leftrightarrow \quad \alpha_{ij}(\tau) = \frac{dC_{ij}}{d\tau}$$

Time from the source fission

Cumulative number of fissions in region i by the time $\tau$ provided by the source fission in region j.
C_{ij} calculation formula

- Non-analog Neutron Transport Monte Carlo Method

- C_{ij} Calculation Formula

\[ C_{ij}(\tau) = \sum_{\tau} \left( \frac{\sigma_{fk}(E_{in})}{\sigma_{tk}(E_{in})} W_{ij}(E_{in}) \right) \]

\[ \sum_{\tau} \left( \frac{W_{sk'(E_0)}}{v_{pk'(E_0)}} \right) \]

Collision Estimator

Neutron Weight

Source Weight W_s

Microscopic fission probability

Cumulative number of fissions in region i by the time \( \tau \).

The number of the source fissions in region j.
Space dependent kinetic calculation

Kinetic analysis code using $C_{ij}$ has been developed.

$$N_i(t) = \sum_{j=1}^{n} \int_{-\infty}^{t} \alpha_{ij}(t - t') N_j(t') dt'$$

$$\approx \sum_{j=1}^{n} \left\{ N_j \left[ C_{ij}(\tau') \right]^{k_{cut}\Delta t} + \sum_{k'=0}^{k-1} N_j(k' \Delta t) \left[ C_{ij}(\tau') \right]^{(k-k')\Delta t} \right\}$$

1. Based on the integral transport equation
2. Forward difference
3. Stepwise reactivity insertion from critical condition in low power
4. No delayed neutrons
5. Temperature dependent $C_{ij}(\tau)$ for feedback effect
6. Temperature rise by fission power
7. $C_{ij}(\tau)$ by modified MVP2.0($\nu_p$ eigenvalue calculation)
Calculation geometry of high-enriched uranium reactor

Region Enrichment
Pulse cores 100.0wt%
U coating 100.0wt%

Initial power 1W

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time step $\Delta t$</td>
<td>$1.0 \times 10^{-7}$ s</td>
</tr>
<tr>
<td>$K_{\text{eff}}^P (300K)$</td>
<td>1.0157</td>
</tr>
<tr>
<td>$K_{\text{eff}}^P (800K)$</td>
<td>1.0026</td>
</tr>
</tbody>
</table>
Calculation geometry of low-enriched uranium reactor

<table>
<thead>
<tr>
<th>Region</th>
<th>Enrichment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse cores</td>
<td>20.0wt%</td>
</tr>
<tr>
<td>U coating</td>
<td>20.0wt%</td>
</tr>
</tbody>
</table>

Initial power: 1W

<table>
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<tr>
<th>Time step $\Delta t$</th>
<th>$1.0 \times 10^{-7}$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\text{eff}}^p (300K)$</td>
<td>1.008</td>
</tr>
<tr>
<td>$K_{\text{eff}}^p (800K)$</td>
<td>0.9997</td>
</tr>
</tbody>
</table>
Fission power in each region

1. Delay of power peak in outer region
2. Delay of power peak in low enriched uranium reactor
3. Power in laser cell region

$k_{eff}^p = 1.008$

$P [W]$

$0.00$ $0.02$ $0.04$ $0.06$ $0.08$ $0.10$

$t [s]$
Peak power density in laser cell tubes

High-enriched uranium reactor

<table>
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<tr>
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<th>Inner region</th>
<th>Outer region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power density [W/cm³]</td>
<td>1.2x10³</td>
<td>6.2x10²</td>
</tr>
<tr>
<td>Full width at half maximum [s]</td>
<td>4x10⁻³</td>
<td>4x10⁻³</td>
</tr>
<tr>
<td>Delay of power peak [s]</td>
<td>-</td>
<td>1x10⁻⁴</td>
</tr>
</tbody>
</table>

Low-enriched uranium reactor

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<th>Inner region</th>
<th>Outer region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power density [W/cm³]</td>
<td>9.2x10²</td>
<td>3.4x10²</td>
</tr>
<tr>
<td>Full width at half maximum [s]</td>
<td>9x10⁻³</td>
<td>9x10⁻³</td>
</tr>
<tr>
<td>Delay of power peak [s]</td>
<td>-</td>
<td>2x10⁻⁴</td>
</tr>
</tbody>
</table>

- **Threshold of laser pumping in Ar-Xe laser gas**
  - About 10 W/cm³ by Russian report
Conclusions

• Kinetic analyses based on the method for weakly coupled systems were performed for a nuclear pumped laser experiment reactor.

• The calculation results show that it is possible to provide enough energy to the laser gas medium in the cell tubes not only in the reactor with highly enriched uranium but also in the reactor with low enriched uranium.
Conclusions (continued)

• It is also possible to provide enough energy to both the laser cell tubes in the inner region and the tubes in the outer region, far from the pulse cores.

• It was also found that there was some delay of the peak of the power in the cell tubes in the outer region, which was caused by neutron thermalization and diffusion in the thermal laser module.

• It was shown that performing NPL experiments using the pulse reactor concept with low-enriched uranium was possible.