Criticality evaluation of a transport cask of irradiated nuclear fuel samples according to the IAEA Regulations for the Safe Transport of Radioactive Material

Mahdi Rezaian, Abedin Pasandi & Hamidreza Mohajerani
Atomic Energy Organization of IRAN (AEOI)
Contents

• Introduction
• Criticality Safety of Transport Cask
• Criticality Evaluation
• Results and Discussion
• Summary and Conclusions
Introduction
• Population of more than **77 million** and area of **1,648 million km²**
• Nominal capacity of electricity generation has reached to more than **78 GWe** last year
• The electric power required in 2025 is expected to reach as high as **195 GWe**

• The government announced the target of **5000 MW** of installed capacity from renewable power plants in the **next five years**

• The government is determined to enhance the nuclear power plants to **20,000 MW** in **next 30 years**

Nominal capacity of electric power generation (last year)
• Iran's nuclear program began in the 1950s.
• AEOI has already various programs in different fields such as electricity generation, medical and industrial radioisotopes, R&D, etc.
✓ Tehran Research Reactor (TRR) → 15 MW, working from 1967
✓ Arak Research Reactor (IR-20 / KHRR) → 20 MW, under construction

Can be utilized for **nuclear fuel development and qualification**
Criticality Safety of Transport Cask
• In this study, it is assumed that five mini plates or six fuel rod samples within a capsule were irradiated in the research reactor.

• TRR mini plates and fuel rod samples of Bushehr Nuclear Power Plant (BNPP) with shorter active length (about 56 cm height)
Capsule containing mini plates or fuel rod samples
The main design aspects of transport casks:

- Structural/Containment [1]
- Criticality [2, 3]
- Shielding [4]
- Thermal [5]
IAEA Safety Standards and Guides

&

Iran’s Nuclear Regulatory Authority (INRA) Regulations
Requirements are imposed to ensure that packages with fissile material contents (e.g. irradiated fuel samples) will remain subcritical under normal and accident conditions of transport.

The cask in this study is categorized as Type B(U)F package and shall be transported so as to meet the requirements of Paras 676 – 686, unless the material is excepted by Para. 674 or 675.

According to these requirements and preliminary calculations, criticality assessment is needed for the cask containing fuel rod samples.
Criticality Evaluation

Diagram of an uncontrolled chain reaction.
The general relationship for establishing the acceptance criteria in the criticality safety of a cask is:

\[ k_{\text{eff}} + n\sigma \leq 1 - \Delta k_m - \Delta k_u \]

- \( k_{\text{eff}} \) is the calculated multiplication factor;
- \( n \) is the number of standard deviations considered (2 and 3 are common values);
- \( \sigma \) is the standard deviation of the \( k_{\text{eff}} \) value obtained with Monte Carlo analysis;
- \( \Delta k_m \) is a required margin of sub-criticality;
- \( \Delta k_u \) is an allowance for the calculational bias and uncertainty.
\[ k_{\text{eff}} + n\sigma \leq 1 - \Delta k_m - \Delta k_u \]

\( \Delta k_u \) is sum of two separate parts, \( \Delta k_c \) and \( \Delta k_b \);

\( \Delta k_c \) is determined by benchmark calculations

\( \Delta k_b \) is related to the manufacturing tolerances as well as material composition uncertainties.

\( \Delta k_m = 0.05 \) was used, which is recommended by most authors.

The right-hand side is the maximum Upper Subcritical Limit (USL) and given by:

\[ \text{USL} = 1 - \Delta k_m - \Delta k_u = 0.95 - \Delta k_c - \Delta k_b \]
To analyze criticality safety of the cask, the MCNP, a well-known and most widely used Monte Carlo code, was used.

To determine $\Delta k_c$ and $\Delta k_b$, a set of calculations were employed for bias and uncertainty of the $k_{eff}$ and also uncertainty of tolerances associated with diameter, thicknesses, and material specifications.

The subcritical limit for the $k_{eff}$ of the single cask and casks array is determined as: $k_{eff} + 2\sigma < 0.9495$
Results and Discussion

Convergence of the multiplication factor ($k_{eff}$) for the single cask under NCT during the cycles.
### Single Cask

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>$k_{\text{eff}} \pm \sigma$</th>
<th>$k_{\text{eff}} + 2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-0</td>
<td>Water surround the undamaged cask</td>
<td>0.03431±0.00006</td>
<td>0.03443</td>
</tr>
<tr>
<td>s-1</td>
<td>Water surround and flood the damaged cask</td>
<td>0.23251±0.00055</td>
<td>0.23361</td>
</tr>
<tr>
<td>s-2</td>
<td>Water surround and flood the half of the damaged cask while it is placed horizontally</td>
<td>0.21627±0.00055</td>
<td>0.21737</td>
</tr>
<tr>
<td>s-3</td>
<td>Water surround and flood the half of the damaged cask while it is placed vertically</td>
<td>0.11269±0.00034</td>
<td>0.11337</td>
</tr>
</tbody>
</table>
Cask Arrays

a) Case i-0, Pitch=0

b) Case i-1 to i-5, Pitch=0 cm,
   $\rho=0.01, 0.05, 0.1, 0.5, 1$ g/cm$^3$

c) Case i-6 to i-10, Pitch=10 cm,
   $\rho=0.01, 0.05, 0.1, 0.5, 1$ g/cm$^3$

d) Case i-11 to i-15, Pitch=20 cm,
   $\rho=0.01, 0.05, 0.1, 0.5, 1$ g/cm$^3$

e) Case i-16 to i-20, Pitch=30 cm,
   $\rho=0.01, 0.05, 0.1, 0.5, 1$ g/cm$^3$
<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>$k_{\text{eff}} \pm \sigma$</th>
<th>$k_{\text{eff}} + 2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>i-0</td>
<td>NCT, infinite, water acts as reflector, pitch=0 cm</td>
<td>0.04048±0.00003</td>
<td>0.04054</td>
</tr>
<tr>
<td>i-1</td>
<td>HAC, infinite, water acts as reflector and moderator, $\rho=0.01\text{g/cm}^3$</td>
<td>0.28312±0.00034</td>
<td>0.28380</td>
</tr>
<tr>
<td>i-2</td>
<td>HAC, infinite, water acts as reflector and moderator, $\rho=0.05\text{g/cm}^3$</td>
<td>0.27353±0.00032</td>
<td>0.27417</td>
</tr>
<tr>
<td>i-3</td>
<td>HAC, infinite, water acts as reflector and moderator, $\rho=0.10\text{g/cm}^3$</td>
<td>0.26509±0.00033</td>
<td>0.26575</td>
</tr>
<tr>
<td>i-4</td>
<td>HAC, infinite, water acts as reflector and moderator, $\rho=0.50\text{g/cm}^3$</td>
<td>0.24682±0.00032</td>
<td>0.24746</td>
</tr>
<tr>
<td>i-5</td>
<td>HAC, infinite, water acts as reflector and moderator, $\rho=1.00\text{g/cm}^3$</td>
<td>0.24247±0.00032</td>
<td>0.24311</td>
</tr>
<tr>
<td>i-6</td>
<td>Pitch=0cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.01\text{g/cm}^3$</td>
<td>0.25709±0.00032</td>
<td>0.25773</td>
</tr>
<tr>
<td>i-7</td>
<td>Pitch=10cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.05\text{g/cm}^3$</td>
<td>0.24922±0.00032</td>
<td>0.24986</td>
</tr>
<tr>
<td>i-8</td>
<td>Pitch=10cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.10\text{g/cm}^3$</td>
<td>0.24454±0.00032</td>
<td>0.24518</td>
</tr>
<tr>
<td>i-9</td>
<td>Pitch=10cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.50\text{g/cm}^3$</td>
<td>0.23355±0.00031</td>
<td>0.23417</td>
</tr>
<tr>
<td>i-10</td>
<td>Pitch=10cm, HAC, infinite, water acts as reflector and moderator, $\rho=1.00\text{g/cm}^3$</td>
<td>0.23315±0.00031</td>
<td>0.23377</td>
</tr>
<tr>
<td>i-11</td>
<td>Pitch=20cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.01\text{g/cm}^3$</td>
<td>0.24635±0.00031</td>
<td>0.24697</td>
</tr>
<tr>
<td>i-12</td>
<td>Pitch=20cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.05\text{g/cm}^3$</td>
<td>0.24137±0.00033</td>
<td>0.24203</td>
</tr>
<tr>
<td>i-13</td>
<td>Pitch=20cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.10\text{g/cm}^3$</td>
<td>0.23770±0.00030</td>
<td>0.23830</td>
</tr>
<tr>
<td>i-14</td>
<td>Pitch=20cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.50\text{g/cm}^3$</td>
<td>0.23235±0.00030</td>
<td>0.23295</td>
</tr>
<tr>
<td>i-15</td>
<td>Pitch=20cm, HAC, infinite, water acts as reflector and moderator, $\rho=1.00\text{g/cm}^3$</td>
<td>0.23248±0.00032</td>
<td>0.23312</td>
</tr>
<tr>
<td>i-16</td>
<td>Pitch=30cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.01\text{g/cm}^3$</td>
<td>0.24000±0.00031</td>
<td>0.24062</td>
</tr>
<tr>
<td>i-17</td>
<td>Pitch=30cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.05\text{g/cm}^3$</td>
<td>0.23690±0.00032</td>
<td>0.23754</td>
</tr>
<tr>
<td>i-18</td>
<td>Pitch=30cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.10\text{g/cm}^3$</td>
<td>0.23416±0.00031</td>
<td>0.23478</td>
</tr>
<tr>
<td>i-19</td>
<td>Pitch=30cm, HAC, infinite, water acts as reflector and moderator, $\rho=0.50\text{g/cm}^3$</td>
<td>0.23192±0.00032</td>
<td>0.23256</td>
</tr>
<tr>
<td>i-20</td>
<td>Pitch=30cm, HAC, infinite, water acts as reflector and moderator, $\rho=1.00\text{g/cm}^3$</td>
<td>0.23183±0.00031</td>
<td>0.23245</td>
</tr>
</tbody>
</table>
Summary and Conclusions
• The effective multiplication factor of the single cask and the cask array under Normal Condition of Transport (NCT) and Hypothetical Accident Conditions (HAC) were calculated using MCNP code.

• Considering bias and uncertainties, the USL which determines the minimum effective multiplication factor for the sub-criticality of the system was specified.

• Regarding the results, the criticality margin of the single and the array under NCT and HAC was far from the USL and therefore the cask can be transported with the assured safe margin.
References


Thank you for your attention

Question?