Neutronics Analysis of TRIGA Mark II Research Reactor

R. Khan, S. Karimzadeh, H. Böck
Vienna University of Technology
Atominstitute
23-03-2010
Contents

• TRIGA Mark II reactor
• MCNP radiation transport code
• MCNP model of first core
• Validation through local experiments
• Burn-up calculations & its applications to MCNP model
• MCNP model of the current core
• Verification of current core model
• Conclusion and outlook
• References
TRIGA Mark II, Vienna

- Operation since 7th March 1962
- Max. $P_{Th} = 250$ kW
- Max. $(\phi)_{th} = 1 \times 10^{13}$ n/cm$^2$-s$^1$
- Fuel Mat. U-ZrH
- Mixed core (3-types of fuel)
- Current Core Loading = 83 FE(s)
- Peak $P_{Th} = 250$ MW
- Irradiation channels in the core
- Experimental facilities outside reactor core
  - Thermal column
  - Radiographic collimator
  - 4 beam tubes
MCNP Transport Code

• MCNP – Monte Carlo based neutronics behaviour simulating code with continuous energy and generalized 3D geometry capabilities
• General purpose radiation transport code (criticality, neutronics and radiation shielding calculations.)
• It simulates neutron, photon, electron independently and also their coupled behaviours
• Energy range
  – For neutrons: $10^{-11}$ MeV to 20 MeV
  – For photon and electron: 1keV to 1 GeV
• Powerful source cards
• Surface Source Writing (SSW ) capability
• 7- tallies (mesh tally- 3D regions of space)– output results
• ENDF/B-VI and JEFF3.1 nuclear data libraries
MCNP Model (1st core)

Inside the core
- 57 FE(s)
- 3 CR(s)
- 1 CIR
- 1 (Sb-Be) SE
- 27 GE (s)
- 2 pneumatic transfer sys.

Outside the core
- Annular gr. ref.
- Th. Column
- Thermalizing col.
- 4 beam tubes
Model Validation (1st core)

First Criticality Experiment (7th March 1962)

<table>
<thead>
<tr>
<th>FE Position</th>
<th>MCNP (K-eff)</th>
<th>Exp. (K-eff)</th>
</tr>
</thead>
<tbody>
<tr>
<td>56 th FE</td>
<td>0.99788</td>
<td>Sub-critical</td>
</tr>
<tr>
<td>57 th FE</td>
<td>1.00183</td>
<td>1.00114</td>
</tr>
</tbody>
</table>

Measurement = 0.157 $  
Calculation = 0.250 $

GA also confirm this model
## Model Validation (1st core)

### Reactivity Distribution Experiment (12-12-1963)

<table>
<thead>
<tr>
<th>FE No.</th>
<th>Reactivity MCNP ($\phi$)</th>
<th>Reactivity Exp. ($\phi$)</th>
<th>%-diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE (F01)</td>
<td>11.9</td>
<td>10.5</td>
<td>8.4</td>
</tr>
<tr>
<td>FE (2058)</td>
<td>53.6</td>
<td>56</td>
<td>4.3</td>
</tr>
<tr>
<td>FE (2141)</td>
<td>73.4</td>
<td>65</td>
<td>12.9</td>
</tr>
<tr>
<td>FE (2164)</td>
<td>102</td>
<td>80</td>
<td>22.5</td>
</tr>
<tr>
<td>FE (2172)</td>
<td>153</td>
<td>143</td>
<td>6.9</td>
</tr>
</tbody>
</table>
Model Validation (1st core)

Thermal Flux Mapping Experiment
(1964)
Burn-up Calculations
(From 07-03-1962 to 30-06-2009)

i. ORIGEN2 calculations & gamma spectroscopic experiments
ii. Effective material composition applied to the MCNP model
Current Core Model (current core)

i. Addition of new FE(s), over the history of reactor operation (20% SS clad, 70% FLIP)

ii. Incorporation of effective burned fuel composition

iii. Burn up group approximation

iv. SE (F06 to F28)

d. Only one graphite element left

vi. Change of one pneumatic transfer system from F21 to F08.
Model Validation (current core)

Criticality Experiment
29-06-2009

MCNP results of critical experiment

MCNP predicts criticality on 78th FE

Rustam Khan
RRFM2010
### Reactivity Dist. Experiment (02-07-2009)

<table>
<thead>
<tr>
<th>FE no.</th>
<th>MCNP ($\phi$)</th>
<th>Exp. ($\phi$)</th>
<th>%-diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10077</td>
<td>129</td>
<td>148</td>
<td>12.8</td>
</tr>
<tr>
<td>7301</td>
<td>81</td>
<td>68</td>
<td>19.1</td>
</tr>
<tr>
<td>10198</td>
<td>58</td>
<td>56</td>
<td>3.6</td>
</tr>
<tr>
<td>2133</td>
<td>48</td>
<td>50</td>
<td>4.0</td>
</tr>
<tr>
<td>2184</td>
<td>27</td>
<td>26</td>
<td>3.8</td>
</tr>
</tbody>
</table>

**Graph:**
- **Measurements**
- **Experiments**

**Graph Details:**
- Reactivity worth ($\phi$) vs. Ring positions from (B(1) to F(5))
- Points for FE: 10077, 7301, 10198, 2133, 2184

---

Rustam Khan

RRFM2010 13
Model Validation (Current core)

Flux mapping experiment
01-07-2009
Conclusion & Outlook

The initial core MCNP model was developed incorporating all geometrical and material information collected from various sources (TRIGA manual, GA, different users and shipment documents). The model was confirmed at both i.e. global and local levels. The developed model was modified to the current core model employing current core conditions. The current core model was completely verified by three different experiments performed in June-July 2009.

The current core model has been extended to biological shielding including the thermal column, radiographic collimator and 4 beam tubes (BT) and confirmed in the thermal column and BT region.
References

• General Atomic (GA), March 1964. TRIGA Mark II Reactor General Specifications and Description. General Atomic Company, U.S.A.
• Shipment documents from GA, USA.
• Log books of TRIGA Mark II reactor at Atominstitue (from 1962 to 2009)
• A.G. Croff, 1999. A user’s manual for the ORIGEN2 computer code. OAK RIDGE National Laboratory, USA.
• R. Khan, S. Karimzadeh, H. Boeck, TRIGA fuel Burn-up calculations. RRFM 2009, Vienna, Austria.
• R, the environment for statistical computing and graphics http://www.r-project.org/
Thanks for Your Attention!
Extended MCNP Model
## Extended Model Validation

<table>
<thead>
<tr>
<th>Positions</th>
<th>Exp. flux</th>
<th>Cal. flux</th>
<th>Cal/exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2,2)</td>
<td>1.6932E+07</td>
<td>2.0755E+07</td>
<td>1.226</td>
</tr>
<tr>
<td>(2,6)</td>
<td>1.9255E+07</td>
<td>3.7084E+07</td>
<td>1.926</td>
</tr>
<tr>
<td>(2,10)</td>
<td>1.5848E+07</td>
<td>2.0693E+07</td>
<td>1.306</td>
</tr>
<tr>
<td>(4,3)</td>
<td>4.5127E+07</td>
<td>5.0593E+07</td>
<td>1.121</td>
</tr>
<tr>
<td>(4,8)</td>
<td>5.6064E+07</td>
<td>6.0810E+07</td>
<td>1.085</td>
</tr>
<tr>
<td>(6,2)</td>
<td>2.9609E+07</td>
<td>4.4650E+07</td>
<td>1.508</td>
</tr>
<tr>
<td>(6,6)</td>
<td>8.3050E+07</td>
<td>8.3050E+07</td>
<td>1.000</td>
</tr>
<tr>
<td>(6,10)</td>
<td>4.5768E+07</td>
<td>4.4126E+07</td>
<td>0.964</td>
</tr>
<tr>
<td>(8,3)</td>
<td>4.4985E+07</td>
<td>5.2957E+07</td>
<td>1.177</td>
</tr>
<tr>
<td>(8,9)</td>
<td>4.4196E+07</td>
<td>6.3907E+07</td>
<td>1.446</td>
</tr>
<tr>
<td>(10,2)</td>
<td>2.0561E+07</td>
<td>2.2168E+07</td>
<td>1.078</td>
</tr>
<tr>
<td>(10,6)</td>
<td>3.2400E+07</td>
<td>4.2623E+07</td>
<td>1.315</td>
</tr>
<tr>
<td>(10,10)</td>
<td>1.6723E+07</td>
<td>2.2406E+07</td>
<td>1.340</td>
</tr>
</tbody>
</table>
Extended Model Validation

Exp. diffusion length = 10.77 cm
MCNP diffusion length = 9.36 cm
Difference = 13%
Effective Material Composition

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>3% Burnup (pcm)</th>
<th>10% Burnup (pcm)</th>
<th>20% Burnup (pcm)</th>
<th>94-Pu-240</th>
<th>57</th>
<th>216</th>
</tr>
</thead>
<tbody>
<tr>
<td>54-Xe-135</td>
<td>850</td>
<td>899</td>
<td>973</td>
<td>5</td>
<td>57</td>
<td>216</td>
</tr>
<tr>
<td>62-Sm-149</td>
<td>620</td>
<td>638</td>
<td>645</td>
<td>3</td>
<td>17</td>
<td>36</td>
</tr>
<tr>
<td>62-Sm-151</td>
<td>101</td>
<td>222</td>
<td>284</td>
<td>3</td>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td>94-Pu-239</td>
<td>-95</td>
<td>-357</td>
<td>-840</td>
<td>3</td>
<td>9</td>
<td>19</td>
</tr>
<tr>
<td>60-Nd-143</td>
<td>51</td>
<td>178</td>
<td>384</td>
<td>2</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>92-U-236</td>
<td>25</td>
<td>84</td>
<td>168</td>
<td>2</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>61-Pm-147</td>
<td>24</td>
<td>65</td>
<td>102</td>
<td>1</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>45-Rh-103</td>
<td>20</td>
<td>82</td>
<td>179</td>
<td>1</td>
<td>9</td>
<td>31</td>
</tr>
<tr>
<td>54-Xe-131</td>
<td>16</td>
<td>56</td>
<td>118</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>55-Cs-133</td>
<td>14</td>
<td>50</td>
<td>105</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>43-Tc-99</td>
<td>11</td>
<td>38</td>
<td>79</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>60-Nd-145</td>
<td>7</td>
<td>26</td>
<td>55</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>63-Eu-155</td>
<td>6</td>
<td>14</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>pseudo FP</td>
<td>6</td>
<td>21</td>
<td>47</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>62-Sm-152</td>
<td>6</td>
<td>26</td>
<td>64</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*The burnups are 3% (approximately experimental burnup), 10%, and 20%. Contributions to the total reactivity (Δk/k) are shown in relative values as calculated by the WIMSD4 program. Boldfaced numbers represent isotopes that contribute >90% of the total burnup reactivity change.*
<table>
<thead>
<tr>
<th>Group No.</th>
<th>2072 AL8 0.255</th>
<th>2196 AL8 1.669</th>
<th>2177 AL8 2.463</th>
<th>2077 AL8 1.604</th>
<th>2044 ST8 1.931</th>
<th>1045 ST8 1.406</th>
<th>1196 ST8 1.151</th>
<th>1198 ST8 0.464</th>
<th>9200 ST8 0.499</th>
<th>1197 ST8 0.965</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group No. 6</td>
<td>2127 AL8 5.162</td>
<td>2172 AL8 5.190</td>
<td>2145 AL8 5.687</td>
<td>2138 AL8 5.556</td>
<td>2202 AL8 5.558</td>
<td>2169 AL8 5.588</td>
<td>2174 AL8 5.592</td>
<td>2168 AL8 5.630</td>
<td>2160 AL8 5.669</td>
<td>2133 AL8 5.690</td>
</tr>
<tr>
<td>Group No. 8</td>
<td>4305 ST8 7.222</td>
<td>4304 ST8 7.588</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group No. 9</td>
<td>7302 FLIP 8.130</td>
<td>7306 FLIP 8.140</td>
<td>7309 FLIP 8.337</td>
<td>7308 FLIP 8.648</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group No. 10</td>
<td>7307 FLIP 9.677</td>
<td>7305 FLIP 9.795</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group No. 11</td>
<td>7304 FLIP 10.408</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group No. 12</td>
<td>7303 FLIP 11.826</td>
<td>7301 FLIP 11.903</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Introduction

Simple Monte Carlo Example

Evaluate \[ G = \int_{0}^{1} g(x)dx, \] with \( g(x) = \sqrt{1 - x^2} \)

- **Mathematical approach:**
  For \( k = 1, \ldots, N \): choose \( \hat{x}_k \) randomly in (0,1)

  \[ G = (1 - 0) \cdot \text{[average value of } g(x)\text{]} = \frac{1}{N} \cdot \sum_{k=1}^{N} g(\hat{x}_k) = \frac{1}{N} \cdot \sum_{k=1}^{N} \sqrt{1 - x_k^2} \]

- **Simulation approach:**
  "darts game"
  For \( k = 1, \ldots, N \): choose \( \hat{x}_k, \hat{y}_k \) randomly in (0,1),
  if \( \hat{x}_k^2 + \hat{y}_k^2 \leq 1 \), tally a "hit"

  \[ G = \text{[area under curve]} \approx (1 \cdot 1) \cdot \frac{\text{number of hits}}{N} \]
Why we need Temperature dependent cross sections When MCNP deals with continuos energy distribution only?

Ideally
\[
\delta = f (E,T)
\]
MCNP & Temp Dependent XS

\[ \sigma(E, T) \]

\[ E_0 \quad T_1 < T_2 < T_3 \]
MCNP with resonance

- MCNP versions are equipped with
  - $\delta = \delta(E, T_o) \cdot [T_o \text{ is given Temp.}]$
- Current MCNP has no module which can create $\delta(E, T)$ from $\delta(E, T_o)$
- Codes like “HELIOS“ can creat $\delta(E, T)$ from $\delta(E, T_o)$
- NJOY generates cross sections having different temp.
- Current MCNP has no module which can create $\delta(E, T)$ from $\delta(E, T_o)$
MCNP - Electric and Magnetic fields

• Magnetic field tracking with MCNP5
  J. S. Bull1,*, H. G. Hughes1, P. L. Walstrom1, J. D. Zumbro1 and N. V. Mokhov2
Current Core Model