APPLICATIONS
OF
MONTE CARLO CALCULATIONS
in
SGR REACTORS

by
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I. INTRODUCTION

The Sodium Reactor Experiment (SRE) has been described in detail elsewhere. Operation with the second core fuel, which consists of 5 rod thorium-uranium alloy fuel elements containing 7.35 percent $^{235}\text{U}$ by weight, was started in the fall of 1960. Following extensive low power experiments, the reactor power was increased to about 2 megawatts where the first indications of reactor instability were observed. Experimental measurements with an on-line analog simulator showed that the fast power coefficient was positive, rather than negative as the Doppler coefficient of the fuel would lead one to expect. It was suggested that the unexpected positive prompt power coefficient was caused by physical bowing of the fuel rods. The bowing was attributed to the establishment of temperature gradients in the fuel cluster as the power increased. The 5 rods of the fuel cluster were not constrained and temperature gradients in the cladding would cause them to bow outward at their center.

Calculations indicated that bowing could cause an increase in the thermal utilization and lead to a positive power coefficient, so experiments were performed in order to obtain some measurements on the magnitude of the effect. One of the experiments utilized a 5 rod fuel element which was fitted with a special device so that the fuel rods could be bowed while the reactor was critical. This fuel element was inserted into three
different fuel channels in the SRE and measurements were made on
the reactivity change caused by bowing the rods. When this experi-
ment was performed in the center fuel channel the result obtained
for outward bowing of the rods was \(+4.8 \pm 0.4\) cents. Measurements
made in the other channels were in agreement with this result
after making an adjustment for their statistical weight.

The calculations which indicated that bowing could cause
a positive coefficient indicated that an increase in thermal
utilization with bowing was the main contributor to the reactivi-
ity effect. These calculations made use of a cylinderized model
of the fuel element and two-group reactor theory. Concern was
expressed regarding the reliability of this method for interpret-
ing the results of the experiment. Since the observed result
depends only on a small change in the geometric configuration of
the fuel cluster, it was feared that the use of a cylindrical
table model for the fuel element might obscure the reason
for the reactivity change caused by fuel rod bowing. It was
therefore decided to attempt a Monte Carlo calculation in order
to study this problem because with this method it is possible to utilize a
more accurate model of the fuel element. The magnitude of the observed
effect indicated that there should be a substantial change in the thermal
flux distribution when the rods were bowed if this was the main
contributor to the reactivity change.
II. MONTE CARLO CALCULATIONS

The geometry for the problem that was solved is shown in Figure 1. Because of symmetry, only half of the hexagonal lattice cell was used in the calculation and the outer boundaries were made totally reflecting. The moderator can, fuel clad, bond and wire wrap were omitted in the interest of simplicity. Aluminum cross sections were used in the coolant channel in place of those for sodium. It is believed that these approximations do not have a large effect on the change in the flux distribution caused by bowing.

A calculation was made with the fuel rods in their normal position where their centers were on a circle of 0.75 inches radius. This calculation was then repeated with the rods spread so that their centers were on a circle of 0.92 inches radius.

Calculations were made for both the thermal and resonance flux distributions. In the thermal calculation the source was distributed uniformly in the graphite at an energy of 2 ev. Flux tallies were started after 15 microseconds, so that on the average each particle made about 8 collisions and slowed down to about 0.54 ev before it contributed to the flux. Particles were followed for 1000 microseconds or until absorbed. In the resonance calculation the source was distributed uniformly in the graphite at an energy of 100 kev. Flux tallies were started after 0.01 microseconds, so that on the average each particle slowed down to about 77 kev before it contributed to the flux.
Each particle was followed until its energy dropped below 0.414 ev or until it was absorbed.

The Monte Carlo portion of the RBU code was used in making these calculations. Neutron thermalization was treated by means of the heavy gas model, and isotopes whose mass was greater than 30 atomic mass units were assumed to cause no change in the neutron energy in scattering. The effective mass for carbon in the thermalization process was taken to be 27 atomic mass units and the temperature used for all materials was 20°C. Resonance cross sections for the fuel were calculated using single level Breit-Wigner formulas and applying Doppler broadening appropriate to 20°C. The resonance cross sections used in RBU are point values calculated for each neutron energy as needed, not effective values. Group cross sections are used outside of the resonance energy region which may cover a different energy range for each isotope present. The cross section library used in the resonance calculation contained 15 groups while that used in the thermal calculation contained 18 groups.

For each of the thermal calculations the running time on the IBM 7090 averaged 137 minutes and about 286,000 collisions were processed. For the resonance calculation with fuel rods in their normal position the running time was 122 minutes and 250,600 collisions were processed.
III. MONTE CARLO RESULTS

Figure 2 shows the ratios of the average thermal flux in the graphite to that in the fuel, and of the average thermal flux in the graphite to that in the aluminum, plotted vs the number of source particles tracked. This provides a means of judging the convergence of the calculations. Although it is evident that the convergence is not as good as would be desirable, it seems clear that spreading the fuel rods does cause a significant change in the thermal flux distribution. Table I gives the values obtained for the thermal flux in each region relative to that in the fuel. Also shown is the average neutron velocity in units of 2200 meters per second.

Figures 3 and 5 show the relative resonance flux per unit lethargy in 5 regions for each of the resonance calculations. Although the minor swings are probably due to statistical fluctuations in the calculations, it appears that the major trends are considerably greater than could be accounted for in this manner. The degree of convergence of the flux in the fuel can be assessed from Figures 4 and 6. Figure 4 shows the flux in the fuel obtained for two separate runs for the rods-normal case while Figure 6 shows the flux in two different fuel rods for the rods-spread case. It is apparent that the major trends are considerably greater than the statistical differences shown in these two figures.
Figure 7 shows the ratio of the average resonance flux in the graphite to that in the fuel summed over all energy groups. Also shown is the relative resonance absorption in thorium for the two cases normalized to a total cell flux of $10^5$ neutrons per cm$^2$ per microsecond. Table II gives the relative absorption rates in each fuel isotope for the two cases. The fission rate in U$^{235}$ was obtained from the calculated absorption rate with the assumption that $\alpha_{25} = 0.45$ was not altered by spreading the fuel rods.
IV. APPLICATION TO THE SRE BOWING EXPERIMENT

The change in the infinite multiplication constant produced by spreading the fuel rods was evaluated using the results of the Monte Carlo calculations where applicable. The following expression for $k_{inf}$, which includes explicitly the effect of non-thermal fission, was used:

$$k_{inf} = k_{th} + k_{epi} = \gamma \epsilon f \rho + (1 - \rho) \frac{\Delta \rho}{\rho} \epsilon_{epi} R$$

where $\rho = \text{probability that a fission neutron becomes thermal}$, and includes the effect of all non-thermal absorption.

$R = \text{non-thermal fission rate} + \text{non-thermal absorption rate in all isotopes}.$

Other symbols have their standard meaning. Since $\gamma, \epsilon$ and $\rho$ are for all practical purposes independent of rod spreading, the change in $k_{inf}$ due to rod spreading can be expressed as

$$\Delta k_{inf} = k_{th} \frac{\Delta f}{f} + \left( k_{th} - \frac{f}{\rho} k_{epi} \right) \frac{\Delta \rho}{\rho} + k_{epi} \frac{\Delta R}{R}$$

The calculation of $f$, $\rho$, $R$ and their changes is the next step. In order to utilize the results of the Monte Carlo calculation, an adjustment to the actual SRE lattice cell size was required since the outer dimension of the Monte Carlo cell was
less than that of the SRE cell. A means of obtaining the relative flux in the fuel cladding, moderator cans, etc., was also needed.

In the case of the thermal flux, this adjustment was made by utilizing the results of S(5) flux calculations for the cylinder-ized SRE cell using cell radii of 12.70 cm and 14.71 cm. A comparison of the results of these two calculations enabled the required adjustments to be made. The adjusted fluxes and the results of the thermal utilization calculation are given in Table III.

The Monte Carlo calculation performed did not provide sufficient information for the calculation of the resonance escape probability for the SRE lattice, so it was necessary to use other means to obtain this quantity. However, before doing this it is of interest to calculate a partial resonance escape probability for the Monte Carlo problem. This can be obtained by taking the ratio of the cell-integrated slowing down density at a high energy to that at an energy near the lower energy cut-off for the resonance flux calculation. An alternate procedure is to use the expression

$$\beta = e \frac{V_f \langle \rho \rangle_{\text{res}}}{V_m \langle \rho \rangle_{\text{sl}}},$$

where $\langle \rho \rangle_{\text{res}}$ is the effective resonance integral over the energy range bounded by the two energies at which the above slowing down densities are evaluated. The results are shown in Table IV and
the difference between the two values obtained is very striking. This difference appears to be due to the resonance flux in the graphite being considerably greater than that in the fuel. An estimate of this effect can be obtained by multiplying the exponent in the equation for \( p \) by the ratio of the average resonance flux in the graphite to that in the fuel as obtained in the Monte Carlo calculation. Although the use of an average flux over the entire resonance range is not strictly correct, it is evident from the result shown in Table IV that this removes most of the discrepancy.

The effective resonance integrals over the resonance ranges used in the Monte Carlo calculation are shown in Table V. These were calculated over the energy ranges listed by using the ARES code (6). The rubber band surface was used in determining the effective surface of the fuel cluster. The ratio of the resonance absorption rate per atom divided by the average flux in the fuel can be defined as an effective resonance cross section. Although this ratio is not strictly the effective resonance integral, it is of interest to compare these values with those of the corresponding partial effective resonance integrals as calculated by the ARES code. This comparison is shown in Table V.

For the SRE calculations, the total effective resonance integrals for each fuel isotope, and the changes due to rod spreading, are shown in Table VI. The value given for thorium
was obtained using Hellstrand's experimental results and the value for $^{235}\text{U}$ was renormalized so as to be consistent with a dilute resonance integral of about 450 barns. The cutoff energy is 0.414 ev. The change in each value due to rod spreading was calculated with the ARES code.

The value obtained for the resonance escape probability in the SRE lattice is given in Table IV. The ratio of the resonance flux in the fuel to that in the moderator was obtained from the Monte Carlo result by adjusting to the SRE cell size with the assumption that the flux in the added graphite was the same as that in region 8 of the Monte Carlo calculation.

The results obtained in the computation of $k_{ro}$ and its change due to rod spreading are given in Table VII. The non-thermal relative absorption rates for the fuel isotopes were assumed to be the same as those obtained in the Monte Carlo calculation. The value obtained for $k_{ro}$ is in good agreement with the value 1.312 obtained by R. W. Keaten.

If the fuel rod spreading occurs uniformly over the entire core, the accompanying reactivity change is given by $\Delta k_{ro}/k_{ro}$ if it is assumed that rod spreading does not alter the leakage. The reactivity increment thus obtained due to spreading the rods in all the fuel elements is 0.615 percent or 0.88 dollars using $\beta_{eff} = 0.70$. The measured statistical weight of the center fuel element is 0.0395 normalized to unity for the entire core. This leads to the value of 3.5 $\Delta k$ for the reactivity increase due to rod spreading in the central element alone. The value obtained
in the bowing experiment was 4.8 $\xi$. In view of the statistical uncertainties in the Monte Carlo calculations and of the necessity for making adjustments to the SRE lattice cell size, the agreement of these two values is considered to be satisfactory.

The calculated value of 3.4 $\xi$ was obtained for the case where the rods are spread without bowing. Since neither the dependence of $\Delta_{\text{eff}}$ on rod displacement nor the actual shape of the bowed rod is accurately known, it is not possible to calculate a correction for this shape factor. It is believed that such a correction would be about 20 percent.
V. OTHER PROBLEMS SOLVED

Solutions for several other problems have been obtained using the RBU Monte Carlo code. Table VIII gives the results for four problems, along with solutions obtained by other means for comparison. The comparisons were made in order to demonstrate that the Monte Carlo code gave reliable results.

The first problem consisted of a uranium fuel rod surrounded by a cylindrical graphite moderator region. A one-velocity calculation was made using 2200 meter per second cross sections with both the 54 and Monte Carlo codes. The second problem was the same as the first except that the energy dependence was introduced. The THERMOS code (7) was used to obtain the solution for comparison. Unfortunately the cross section library used in THERMOS is not quite the same as that used in the Monte Carlo code, so this comparison is somewhat spoiled. Nevertheless it is evident that the two results are in fairly good agreement.

The third problem was a seven-rod SRE core I uranium fuel cluster in a square graphite lattice of 7 inch pitch. Experimental thermal flux measurements were available for this problem (8). Monte Carlo calculations were made using an effective mass of 12, 24, and 30 atomic mass units for carbon in neutron thermalization. The neutron source was uniformly distributed in the graphite at an energy of 2 electron volts. It is apparent that an effective carbon mass slightly larger than 24 would result in good agreement.
with the experimental flux measurement. It was because of this that the value 27 was chosen for use in the 5 rod fuel cluster calculations.

The fourth problem was a calculation of the age to 1.46 eV of fission neutrons in diphenyl. A point source in an infinite diphenyl medium was used so that the age calculation could also be made using the TYCHE code for comparison (9). Ten-thousand particles were tracked and the IBM 7090 computing time was 30 minutes. It is seen that the agreement between the RBÜ and TYCHE results is quite good.
VI. CONCLUSION

The Monte Carlo calculations show that the observed reactivity increase due to fuel rod bowing in SRE can be accounted for by the accompanying change in thermal flux distribution. Comparison of results obtained from the RBU Monte Carlo code with those calculated by other means or obtained from experiment shows that the Monte Carlo results are reliable. The examples given here illustrate the capability of the Monte Carlo method for making reactor calculations. An important advantage of the Monte Carlo method is that the physical and geometrical models used in the calculations for reactor lattices are closer approximations to the actual situation than are the models that are usually employed with other methods. In particular, fuel clusters can be put in without the necessity of representing them by hollow cylinders or homogenization. Two important disadvantages of the Monte Carlo calculations are the statistical uncertainty in the result that is obtained and the long computing time that is required to obtain even a moderately good result.
VII. REFERENCES


FIGURE CAPTIONS

Figure 1 - Cell Geometry for the 5 rod Monte Carlo Calculation.

Figure 2 - Thermal Flux Ratio vs Number of Particle Histories.

Figure 3 - \( \phi(u) \) in Cell Regions with Fuel Rods Normal.

Figure 4 - \( \phi(u) \) in Fuel for Two Separate Runs with Fuel Rods Normal.

Figure 5 - \( \phi(u) \) in Cell Regions with Fuel Rods Spread.

Figure 6 - \( \phi(u) \) in Each of Two Fuel Rods with Fuel Rods Spread.

Figure 7 - Total Resonance Flux and Resonance Absorption in Th\textsuperscript{232} Below 1.234 ev vs Number of Particle Histories.


<table>
<thead>
<tr>
<th>Region</th>
<th>Material</th>
<th>( \phi )</th>
<th>( \frac{\nabla \phi}{\nabla \phi} )</th>
<th>( \phi )</th>
<th>( \frac{\nabla \phi}{\nabla \phi} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stainless</td>
<td>1.033</td>
<td>2.01</td>
<td>1.470</td>
<td>1.81</td>
</tr>
<tr>
<td>2,3,4</td>
<td>Fuel</td>
<td>1.000</td>
<td>1.97</td>
<td>1.000</td>
<td>1.94</td>
</tr>
<tr>
<td>5</td>
<td>Aluminum</td>
<td>2.612</td>
<td>1.64</td>
<td>2.091</td>
<td>1.66</td>
</tr>
<tr>
<td>6,7,8</td>
<td>Graphite</td>
<td>5.511</td>
<td>1.54</td>
<td>5.264</td>
<td>1.53</td>
</tr>
</tbody>
</table>

(E cutoff = 0.414 ev.)

\[
\phi = \phi_0 \int_0^{E_c} n(E) dE
\]
## TABLE II

**Non-thermal Relative Reaction Rates in Fuel**

<table>
<thead>
<tr>
<th>Absorption</th>
<th>Rods Normal</th>
<th>Rods Spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{U}^{238}$</td>
<td>2.90</td>
<td>3.08</td>
</tr>
<tr>
<td>$\text{U}^{235}$</td>
<td>108.5</td>
<td>110.5</td>
</tr>
<tr>
<td>$\text{Th}^{232}$</td>
<td>70.4</td>
<td>74.0</td>
</tr>
</tbody>
</table>

Fission (Assume $\alpha_{25} = 0.45$)

| $\text{U}^{235}$ | 74.8 | 76.2 |

$R = \frac{F}{A}$  
0.4114  
0.4062
### TABLE III

**Thermal Utilization for SRE**

<table>
<thead>
<tr>
<th>Material</th>
<th>Vol Fr.</th>
<th>$\tilde{\rho}_n$ (cm$^{-1}$)</th>
<th>$\Phi$</th>
<th>Abs.</th>
<th>Rods Normal $\Phi$</th>
<th>Abs.</th>
<th>Rods Spread $\Phi$</th>
<th>Abs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless</td>
<td>0.00105</td>
<td>0.2485</td>
<td>1.033</td>
<td>0.269</td>
<td>1.470</td>
<td>0.383</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>0.02096</td>
<td>1.6019</td>
<td>1.0</td>
<td>33.569</td>
<td>1.0</td>
<td>33.569</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaK</td>
<td>0.00117</td>
<td>0.0309</td>
<td>1.85</td>
<td>0.067</td>
<td>1.48</td>
<td>0.053</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless</td>
<td>0.00162</td>
<td>0.2485</td>
<td>1.85</td>
<td>0.744</td>
<td>1.48</td>
<td>0.595</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>0.02666</td>
<td>0.0120</td>
<td>2.61</td>
<td>0.837</td>
<td>2.09</td>
<td>0.670</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconium</td>
<td>0.00278</td>
<td>0.0082</td>
<td>3.30</td>
<td>0.075</td>
<td>3.15</td>
<td>0.072</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite</td>
<td>0.87950</td>
<td>0.00424</td>
<td>5.814</td>
<td>2.168</td>
<td>5.553</td>
<td>2.071</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconium</td>
<td>0.01175</td>
<td>0.0082</td>
<td>6.03</td>
<td>0.583</td>
<td>5.76</td>
<td>0.556</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>0.03725</td>
<td>0.0120</td>
<td>6.03</td>
<td>2.701</td>
<td>5.76</td>
<td>2.579</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless</td>
<td>0.00112</td>
<td>0.2485</td>
<td>6.03</td>
<td>1.676</td>
<td>5.76</td>
<td>1.601</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Void</td>
<td>0.01614</td>
<td>0.0</td>
<td>6.03</td>
<td>0.0</td>
<td>5.76</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ f = 0.78636 \quad \text{or} \quad 0.79644 \]
### TABLE IV

Resonance Escape Probability

<table>
<thead>
<tr>
<th>Expression</th>
<th>Monte Carlo Prob.</th>
<th>SRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K = \frac{V_f}{V_m \int \phi \leq \phi_{sm}}$</td>
<td>0.499</td>
<td>0.387</td>
</tr>
<tr>
<td>$\frac{\phi_f}{\phi_m}$</td>
<td>0.732</td>
<td>0.680</td>
</tr>
<tr>
<td>$p = \xi \leq \phi_{res}$</td>
<td>0.569</td>
<td>0.662</td>
</tr>
<tr>
<td>$p = e$</td>
<td>0.662</td>
<td>0.755</td>
</tr>
<tr>
<td>$p = \frac{Q(u2)}{Q(u1)}$</td>
<td>0.687</td>
<td>0.554</td>
</tr>
</tbody>
</table>
### TABLE V

<table>
<thead>
<tr>
<th></th>
<th>ARES RI</th>
<th>Monte Carlo $\sigma$</th>
<th>Energy Range $E_{\text{min}}$</th>
<th>$E_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th$^{232}$</td>
<td>6.09 b</td>
<td>5.95 b</td>
<td>10.1 ev</td>
<td>1,234 ev</td>
</tr>
<tr>
<td>$\text{U}^{238}$</td>
<td>127.4</td>
<td>104.5</td>
<td>4.56</td>
<td>3,355</td>
</tr>
<tr>
<td>$\text{U}^{235}$</td>
<td>106.2</td>
<td>93.5</td>
<td>1.37</td>
<td>33.7</td>
</tr>
</tbody>
</table>

$\overline{\sigma} = \text{Absorption Rate per atom}$

$$V_{f} \int_{E_{\text{min}}}^{E_{\text{max}}} \varphi(E) dE$$
**TABLE VI**

Effective Resonance Integrals for SRE

<table>
<thead>
<tr>
<th></th>
<th>RI</th>
<th>RI due to Spreading Rods</th>
<th>(N \times 10^{-24})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th(^{232})</td>
<td>10.45 b</td>
<td>0.30 b</td>
<td>0.02872</td>
</tr>
<tr>
<td>U(^{238})</td>
<td>131</td>
<td>6.15</td>
<td>0.00217</td>
</tr>
<tr>
<td>U(^{235})</td>
<td>544</td>
<td>3.71</td>
<td>0.00016</td>
</tr>
</tbody>
</table>

\(T = 20\,^\circ\text{C}\). \(E_c = 0.414\,\text{ev}\).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta )</td>
<td>1.778</td>
<td></td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>1.010</td>
<td></td>
</tr>
<tr>
<td>( f )</td>
<td>0.7864</td>
<td>( \Delta f/f = +0.01282 )</td>
</tr>
<tr>
<td>( p )</td>
<td>0.7553</td>
<td>( \Delta p/p = -0.00808 )</td>
</tr>
<tr>
<td>( R )</td>
<td>0.4114</td>
<td>( \Delta R/R = -0.01271 )</td>
</tr>
<tr>
<td>( \gamma_{\text{epi}} )</td>
<td>2.44</td>
<td></td>
</tr>
</tbody>
</table>

\( k_\infty = 1.314 \) \quad \frac{\Delta K_\infty}{K_\infty} = +0.00615

Statistical weight of center fuel element = 0.0395

\( \Delta \rho_{\text{center fuel rod}} = 0.000240 = 3.47 \% \)

Measured value = 4.8 \pm 0.4 \%
### TABLE VIII

Comparison of Monte Carlo Results with Those Obtained by Other Means

<table>
<thead>
<tr>
<th>Quantity Computed</th>
<th>RBU Result</th>
<th>Other Method</th>
<th>Other Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_m$</td>
<td>3.17</td>
<td>s4</td>
<td>3.21</td>
</tr>
<tr>
<td>$\Phi_f$</td>
<td>2.63</td>
<td>THERMOS</td>
<td>2.53</td>
</tr>
<tr>
<td>$\frac{\Phi_m}{M=12}$</td>
<td>4.44</td>
<td>Experiment</td>
<td>3.77</td>
</tr>
<tr>
<td>$\frac{\Phi_f}{M=24}$</td>
<td>3.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{\Phi_f}{M=30}$</td>
<td>3.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>age</td>
<td>46.23 cm$^2$</td>
<td>TYCHE</td>
<td>46.40 cm$^2$</td>
</tr>
</tbody>
</table>
Figure 2

Thermal Flux Ratio vs Number of Particle Histories
Figure 3

\( \phi (u) \) in Cell Regions with Fuel Rods Normal
\( \phi(u) \) in Fuel for Two Separate Runs with Fuel Rods Normal.

Figure 4

\[ \Delta = 1000 \text{ SOURCE PARTICLES} \]
\[ \bigcirc = 500 \text{ SOURCE PARTICLES} \]
Figure 5

$\phi(u)$ in Cell Regions with Fuel Rods Spread
\( \Phi (u) \) in Each of Two Fuel Rods with Fuel Rods Spread
Figure 7

Total Resonance Flux and Resonance Absorption in $^{232}$Th

8-23-63

7593-1516