Analysis of Standard and FLIP Fuel Mixed Loading Patterns in TRIGA Mark-III Reactor

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Abstract

Mixed standard-FLIP fuel loading patterns in the TRIGA Mark-III reactor were analyzed.

It was judged that the mixed loading pattern with the standard fuel in the B-ring and the FLIP fuel in other rings was mostly desirable in view of fuel temperature, cooling condition with the natural convection, or effective thermal flux utilization in the central thimble.

In addition, the maximum useful flux in the reactor beamports versus the loading patterns was evaluated.

요 약

TRIGA Mark-III 원자로에서 사용하는 표준형 및 FLIP 형 핵연료의 혼합장치 방법을 재계하였다.

점토럴 핵연료 장관방법은 B링에 표준형 그리고 그 외의 팀에는 FLIP 형 핵연료를 장치하는 방법이 핵연료의 운도, 방각제의 자연류 및 central thimble에서의 효율적인 열전달이 흐름에서 가장 바람직한 것으로 제시하였다.

또한 핵연료 장관방법에 따른 beamport 에서의 열전달이 이용에 관해서도 평가하였다.

1. Introduction

The standard fuel\(^{1}\) for the TRIGA reactor is a solid, homogeneous mixture of uranium zirconium hydride alloy (H/Zr ratio of 1.6) containing 8.5 w/o uranium enriched to 20% in U-235. In order to improve the fuel life-time in the core, the FLIP fuel developed through the Fuel Life-time Improvement Program was chosen as the fuel for the TRIGA Mark-III reactor instead of the standard fuel. The FLIP fuel\(^{2}\) contains 8.5 w/o uranium enriched to 70% in U-235 and 1.6 w/o erbium as a burnable poison to increase the core life-time in higher power TRIGA reactors.

TRIGA Mark-III reactor is equipped with a central thimble for conducting experi-
ments or irradiating small sample in the core at the position of maximum flux. The central thimble itself is an aluminum tube filled with water that extends from the bridge straight down through the central hole of the top and bottom grid plates.

It is pointed out that several problems a natural convection cooling system might be brought about by high power at inner side of the B-ring loaded by FLIP fuel elements and great change of power at the boundary between standard and FLIP aels.

In order to analyze the mixed standard-FLIP fuel loading patterns, power distributions in the core, heat fluxes in the coolant channel and minimum DNB ratios, that is, the minimum ratio of the local allowable heat flux to the actual heat flux in the coolant channel, were evaluated under safety conditions of TRIGA Mark-II reactor in operation.

Finally, maximum useful fluxes in the central thimble and beamports were also evaluated. A nuclear reactor core analysis code, CITATION, was used in the calculation of flux distributions.

2. Method of Analysis

2.1 Power Distribution

An initial standard core of TRIGA Mark-II reactor contains about 100 fuel elements including instrumented elements ad the fueled follower control rods. To analyze the fuel loading pattern with conservatism, some mixed loading patterns were selected. On account of peak flux and power density at the core center region, fuel elements at the B or C-ring were replaced with different kind of fuel elements. Table 1 shows six loading patterns under consideration. It was assumed that each core considered with sufficient thickness of water reflector contains 100 fuel elements. And the core aluminum shroud was neglected in these calculations. The model for one-dimensional calculation of CITATION code is shown in Fig. 1.

For one-dimensional diffusion calculations, cell-averaged broad-group cross sections were generated using THERMOSMUG and GCG-4 code as reported in reference 7. In the calculations, 30 thermal energy groups and 99 fast energy groups were collapsed into four thermal groups with the upper energies of 1.125 eV, 0.42

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Ring</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
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<tr>
<td>I</td>
<td>S**</td>
<td>S</td>
<td>S</td>
<td>S</td>
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<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
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</tr>
<tr>
<td>III</td>
<td>S</td>
<td>F</td>
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<td>F</td>
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<tr>
<td>IV</td>
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<td>S</td>
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</tr>
<tr>
<td>VI</td>
<td>F</td>
<td>S</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td></td>
</tr>
</tbody>
</table>

*S: Standard fuel
**F: FLIP fuel

![Fig. 1. One Dimensional Model of TRIGA Mark-II Loaded by 100 Fuel Elements (Unit: cm)](image)
eV, 0.14 eV and 0.05 eV, and three fast
groups with the upper energies of 15 MeV, 
608 KeV and 9.15 KeV, respectively. To 
study the effect of one fuel element 
surrounded by different kind of fuel 
elements, a model where a specific fuel 
element is centered in the Case I and 
Case II was considered.

2.2 Heat Flux in the Coolant Channel

The active part of a fuel element is 
approximately 3.63 cm in diameter and 
38.1 cm in length. The heat generated 
from the fuel rod is almost transferred to 
the radial direction. Assuming the fuel 
rod is infinitely long, the heat flux trans-
ferred into the collant channel, \( q'' \), is 
given by

\[ q'' = \frac{A^2}{2(A+B)} q''' \]

where,

- \( q''' \) = power density of fuel rod
- \( A \) = radius of fuel rod
- \( B \) = thickness of cladding material

With the volume ratio of unit cell to 
fuel rod, the overall (both radial and 
axial) peak-to-average power generation 
ratio and cell homogenized power density, 
the maximum power density of fuel rod 
in the core is calculated.

2.3 Minimum DNB ratio

Related to the reactor safety for the 
mixed loading pattern, minimum DNB 
ratios are calculated as follows: According 
to the safeguards analysis report for the 
TRIGA Mark-II reactor, the critical (or 
burnout) heat flux with the design cooling 
water temperature at the core inlet (32.2°C) 
is 395,000 BTU/hr-ft². For a 100 fuel 
element core with an overall peak-to-
average power density ratio of 2.0 (1.6 
for radial and 1.25 for axial), this heat 
flux corresponds to a maximum reactor 
power of 2.7 MW. And the minimum DNB 

cratio at 2.0 MW power is 1.6.

Therefore, each minimum DNB ratio, 
MDNBR, on mixed loading patterns is 

\[ \text{MDNBR} = \frac{D_s \times M_t}{M_f} \]

where,

- \( D_s \) = minimum DNB ratio of standard 
core at 2.0 MW power (1.6)
- \( M_t \) = maximum heat flux of standard 
core at 2.0 MW power
- \( M_f \) = maximum heat flux of considered 
core

3. Results and Discussion

The analyzed results on the flux and 
power distributions for six cases are shown 
in Fig. 2 through Fig. 5.

Thermal fluxes of the FLIP core are 
significantly different from those of the 
standard core while fast fluxes are 
generally similar to those of the standard 
core. Fig. 2 shows thermal fluxes below 
the energy of 0.05 eV on Case I through 
Case IV. It is shown that the thermal flux 
of the FLIP core (Case IV) is on account 
of the higher enrichment of FLIP fuel 
lower than that of the standard core (Case 
I). Fig. 2 also shows that the thermal 
fluxes in the central thimble on Case III 
and Case IV are ~40% and ~10% lower 
than that on Case I, respectively.

In view of maximum useful thermal flux 
in the reactor beamports, spatial thermal 
flux distribution in the reflector region 
plays important role because the flux 
depends on the spatial distance from 
outside edge of the core. In the reflector
Fig. 2. Radial Thermal Flux Distributions for Case I through Case IV

Fig. 3. Radial Power Distributions of Standard and FLIP Core (Case I and Case II)

Fig. 4. Radial Power Distributions of Mixed Standard-FLIP Cores (Case III and Case IV)

Fig. 5. Radial Power Distributions of Mixed Standard-FLIP Cores (Case V and Case VI)

region, thermal fluxes, neutron energy less than 0.05 eV, at distance of 1.27 cm (1/2"), 2.54 cm (1") and 3.81 cm (1-1/2") from the edge of the FLIP core decrease

~28.3%, ~14.5% and ~7% comparing with those of the standard core, respectively. As the distance increases further, the thermal flux on Case II approaches to that
Table 2. Maximum Power Density of Ring and Maximum Heat Flux in the Coolant Channel.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Description</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Power density (w/cm²)</td>
<td>105.44</td>
<td>89.46</td>
<td>77.00</td>
<td>60.51</td>
<td>43.86</td>
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<td>Heat Flux (BTU/hr-ft²)</td>
<td>296,219</td>
<td>251,330</td>
<td>216,331</td>
<td>169,984</td>
<td>123,224</td>
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<td>II</td>
<td>Power density (w/cm²)</td>
<td>107.91</td>
<td>95.68</td>
<td>74.40</td>
<td>58.74</td>
<td>43.30</td>
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<td>Heat Flux (BTU/hr-ft²)</td>
<td>303,243</td>
<td>268,800</td>
<td>209,008</td>
<td>165,038</td>
<td>121,639</td>
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<td>III</td>
<td>Power density (w/cm²)</td>
<td>83.39</td>
<td>95.92</td>
<td>74.87</td>
<td>59.17</td>
<td>43.58</td>
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<td>Heat Flux (BTU/hr-ft²)</td>
<td>243,275</td>
<td>268,466</td>
<td>210,339</td>
<td>166,243</td>
<td>122,431</td>
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<td>IV</td>
<td>Power density (w/cm²)</td>
<td>137.73</td>
<td>80.84</td>
<td>75.80</td>
<td>59.38</td>
<td>42.86</td>
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<td>Heat Flux (BTU/hr-ft²)</td>
<td>386,928</td>
<td>227,117</td>
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<td>166,813</td>
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<tr>
<td>V</td>
<td>Power density (w/cm²)</td>
<td>89.44</td>
<td>116.93</td>
<td>67.83</td>
<td>59.17</td>
<td>43.96</td>
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<td>Heat Flux (BTU/hr-ft²)</td>
<td>251,256</td>
<td>328,502</td>
<td>190,557</td>
<td>166,243</td>
<td>120,688</td>
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<td>VI</td>
<td>Power density (w/cm²)</td>
<td>127.28</td>
<td>65.15</td>
<td>83.67</td>
<td>58.55</td>
<td>42.86</td>
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<td>Heat Flux (BTU/hr-ft²)</td>
<td>359,571</td>
<td>183,016</td>
<td>235,049</td>
<td>164,499</td>
<td>120,402</td>
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</table>

Original design value is 293,900 BTU/hr-ft².

on Case I. The thermal peak flux in the reflector region appears somewhere between 1.8 cm and 2.6 cm from the core edge. The average flux difference in the above range is ~12%. According to the original design value of the TRIGA Mark II reactor, the radial spacing between the outer ring edge (G-ring) of fuel elements and beamports is 1 inch. Therefore, the thermal flux of the FLIP core at beamports is ~12% lower than that of the standard core. Considering the fuel loading up to F-ring, the flux is reduced by ~35% on Case I and by ~26% on Case II at the beamport.

The thermal flux at the boundary between regions with different kind of fuels in the mixed core has large difference. As shown in case II and Case III, the thermal flux of the FLIP ring increases at the vicinity of the standard ring while that of the standard ring decreases at the vicinity of the FLIP ring. These effects are quite well appeared in power distributions on Case I through Case II. The inner side power density in the B-ring on Case II is ~13.3% higher than that on Case I, and difference of them at the boundary between regions with different kind of fuels of mixed cores is very large. In general, power difference at the boundary between regions with different kind of fuels may be very serious because of cross flow, that is, flow between adjacent channels, in the coolant channel. Fortunately the inner side power density in the B-ring on Case II is decreased below that on Case I.

Table 2 shows power densities of all rings and heat fluxes in the coolant channel at 2.0 MW power level. The calculated maximum heat flux on Case I is 296,219 BTU/hr-ft² (93.44 w/cm²) while the design value of the TRIGA Mark II
reactor is 293,900 BTU/hr-ft² (92.7 W/cm²) as shown in Table 2. The calculated result agrees with the design value in less than \( \sim 1\% \). Maximum heat fluxes on case II and Case V occur in the C-ring while those on others in the B-ring and maximum heat fluxes of all cases except Case II are higher than the design value. Only the maximum power density on Case II is lower than that on standard core.

As shown in Table 3, minimum DNB ratios of all cases except Case II are lower than the design value, that is, 1.6.

In order to evaluate the effect of one fuel element surrounded by different kind of fuels, calculations of power distribution for one FLIP fuel loading in the standard core and for one standard fuel loading in the FLIP core were carried out. The ratio of the ring power density for one FLIP fuel loading in the standard core to that for the standard core is 1.534 while the ratio of the ring power density for one standard fuel loading in the FLIP core to that for the FLIP core is 0.655. One FLIP fuel loading in the standard core makes the power density of the FLIP fuel increase while one standard fuel loading in the FLIP core decrease.

Assuming one FLIP fuel loading in the C-ring of the standard core, the minimum DNB ratio in the coolant channel is \( 1.6 \times 296,219/(251,330 \times 1.534) = 1.23 \). Similarly, the minimum DNB ratio for one FLIP fuel loading in the D and E-ring of the standard core is 1.43 and 1.82, respectively. Then, the minimum DNB ratio for one FLIP fuel loading in the B, C or D-ring of the standard core might be lower than the design value.

4. Conclusion

1) It is judged that the mixed loading pattern with standard fuel in the B-ring and the FLIP fuel in other rings is mostly desirable in view of fuel temperature, or effective thermal flux utilization in the central thimble.

2) In the central thimble, the thermal flux of the FLIP core is \( \sim 40\% \) lower than that of the standard core. and the thermal flux of the mixed core loaded by the standard fuels in the B-ring and the FLIP fuels in other rings is only \( \sim 10\% \) lower.

3) The thermal flux of the FLIP core at beamports is \( \sim 12\% \) lower than that of the standard core. In case of the fuel loading up to F-ring, the thermal flux at beamports is reduced by \( \sim 35\% \) on the standard core and \( \sim 26\% \) on the FLIP core comparing with the loading up to G-ring.

4) One FLIP fuel loading in the standard core leads to very large positive reactivity. Especially, one FLIP fuel loading in the B, C and D-ring of the standard core should be avoided in order to reduce the maximum heat flux in the coolant channel.

In addition, it is desirable that the cross flow between adjacent cooling channels depending on the large power density difference at the boundary between regions with different kind of fuels in mixed cores be analyzed.
Reference