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

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(Received October 29, 1979)

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 FLIP형 핵연료의 혼합장전 방법을 해석하였다.

검토된 핵연료 장전방법중 B링에 표준형 그리고 그외의 링에는 FLIP형 핵연료를 장전하는 방법이 핵연료의 온도, 냉각재의 자연대류 및 central thimble에서의 효율적인 열중성자 이용면에서 가장 바람직함을 입증하였다.

또한 핵연료 장전방법에 따른 beamport에서의 열중성자 이용에 관해서도 평가 하였다.

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-

nents or irradiating small sample in the :ore at the position of maximum flux. The :entral thimble itself is an aluminum tube :illed with water that extends from the)ridge straight down through the central 1ole of the top and bottom grid plates.

It is pointed out[3] that several problems n natural convection cooling system might 1e brought about by high power at inner ide of the B-ring loaded by FLIP fuel lements and great change of power at the oundary between standard and FLIP uels.

In order to analyze the mixed standard-'LIP fuel loading patterns, power distri- utions in the core, heat fluxes in the oolant channel and minimum DNB ratios, 1at is, the minimum ratio of the local llowable heat flux to the actual heat lux in the coolant channel, were evaluated nder safety conditions of TRIGA Mark-Ⅲ 2actor in operation.

Finally, maximum useful fluxes in the 2ntral thimble and beamports were also valuated. A nuclear reactor core analysis)de, CITATION[4], was used in the cal- 1lation of flux distributions.

2. Method of Analysis

2.1 Power Distribution

An initial standard core[1] of TRIGA [ark-Ⅲ reactor contains about 100 fuel ements including instrumented elements nd the fueled follower control rods. To 1alyze the fuel loading pattern with)nservatism, some mixed loading patterns ere selected. On account of peak flux nd power density at the core center 2gion, fuel elements at the B or C-ring ere replaced with different kind of fuel lements. Table 1 shows six loading

Table 1. Standard-FLIP Fuel Loading Pattern

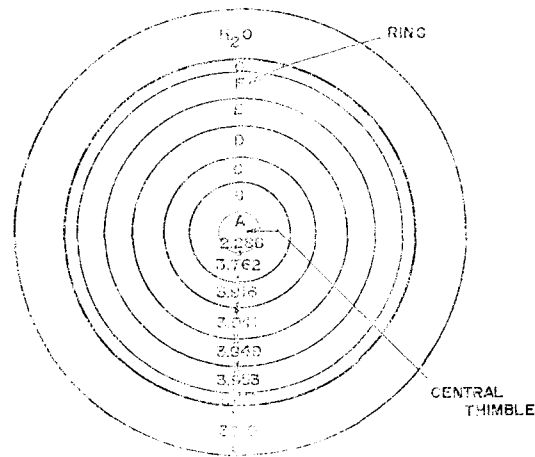| Case No. \ Ring	B	C	D	E	F
I	S*	S	S	S	S
Ⅱ	F**	F	F	F	F
Ⅲ	S	F	F	F	F
Ⅳ	F	S	S	S	S
Ⅴ	S	F	S	S	S
Ⅵ	F	S	F	F	F

*S : Standard fuel
**F : FLIP fuel

Fig. 1. One Dimensional Model of TRIGA Mark-Ⅲ Loaded by 100 Fuel Elements (Unit: cm)

patterns under consideration. It was assu- med 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 calcula- tions, cell-averaged broad-group cross sections were generated using THERMOS-MUG[5] and GGC-4[6] 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

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[1] 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 transferred 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[1], 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 ratio at 2.0 MW power is 1.6.

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

$$MDNBR = \frac{D_n \times M_s}{M_f}$$

where,

D_n = minimum DNB ratio of standard core at 2.0 MW power (1.6)

M_s = 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 II) 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 II and Case III 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
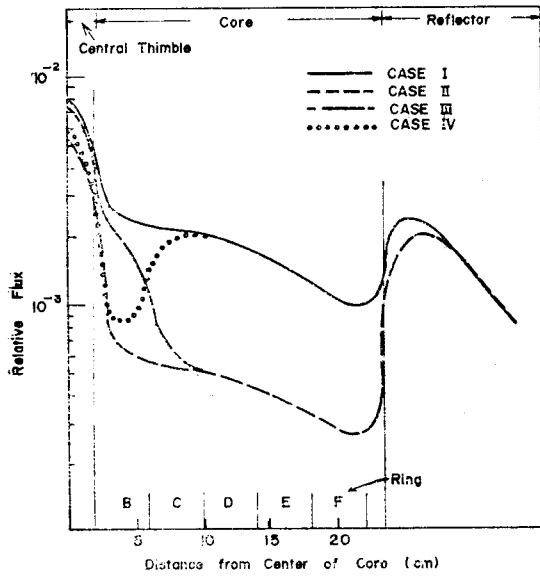
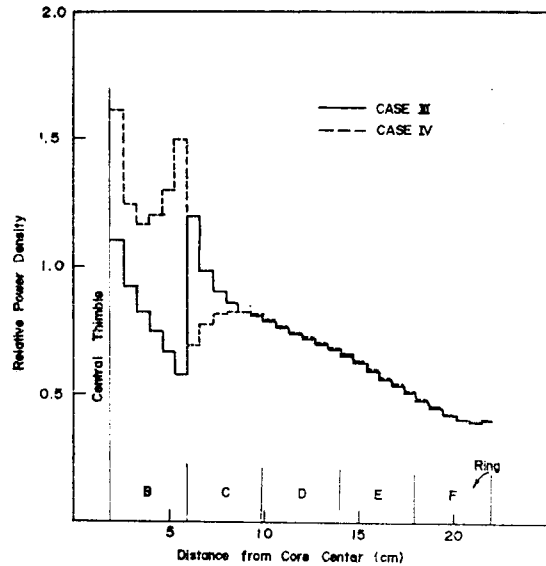**Fig. 2. Radial Thermal Flux Distributions for Case Ⅰ through Case Ⅳ**

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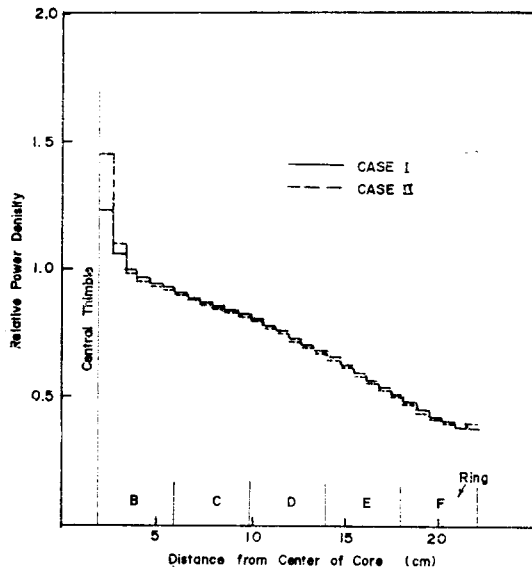

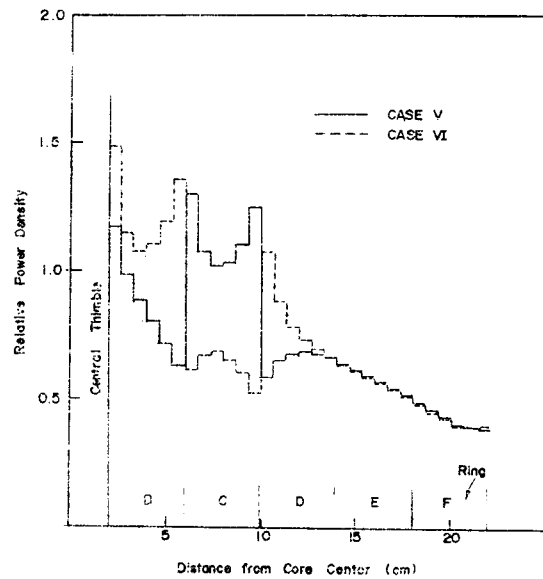**Fig. 3. Radial Power Distributions of Standard and FLIP Core (Case Ⅰ and Case Ⅱ)**

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

$\sim$28.3%, $\sim$14.5% and $\sim$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.

Case No.	Ring Description	B	C	D	E	F
I	Power density (w/cm³)	105.44	89.46	77.00	60.51	43.86
	Heat Flux (BTU/hr-ft²)	296,219	251,330	216,331	169,984	123,224
II	Power density (w/cm³)	107.94	95.68	74.40	58.74	43.30
	Heat Flux (BTU/hr-ft²)	303,243	268,800	209,008	165,038	121,639
III	Power density (w/cm³)	83.39	95.92	74.87	59.17	43.58
	Heat Flux (BTU/hr-ft²)	243,275	269,466	210,339	166,243	122,431
IV	Power density (w/cm³)	137.73	80.84	75.80	59.38	42.86
	Heat Flux (BTU/hr-ft²)	386,928	227,117	212,939	166,813	120,402
V	Power density (w/cm³)	89.44	116.93	67.83	59.17	43.96
	Heat Flux (BTU/hr-ft²)	251,256	328,502	190,557	166,243	120,688
VI	Power density (w/cm³)	127.28	65.15	83.67	58.55	42.86
	Heat Flux (BTU/hr-ft)²	359,571	183,016	235,049	164,499	120,402

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[8]. 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 IV, 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 II through Case IV. 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[1] of the TRIGA Mark-II

Table 3. Minimum DNB Ratio

Case No.	DNBR
I	1.60
II	1.56
III	1.76
IV	1.22
V	1.44
VI	1.32

reactor is 293,900 BTU/hr-ft^2 (92.7 w/cm^2) as shown in Table 2. The calculated result agrees with the design value in less than ~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 III are higher than the design value. Only the maximum power density on Case III is lower than that on standard core.

As shown in Table 3, minimum DNB ratios of all cases except Case III 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× 296,219/(251,330×1.534)=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 ~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 ~10% lower.

3) The thermal flux of the FLIP core at beamports is ~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 ~35% on the standard core and ~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.

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