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Analysis of Fuel Options in TRIGA Reactor

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Abstract

In this paper, nuclear characteristics of TRIGA Mark-III has been analyzed in detail for six different fuel options.

Presently, 70 w/o enriched FLIP fuels are adopted for TRIGA core to improve fuel lifetime. However, such highly enriched fuels are not easily obtained due to nonproliferation treaty. This research examines the possible substitution for FLIP fuels with high density fuels without reducing the nuclear performance. This work will provide long-time plan for TRIGA operation.

요 약

이 논문에서는 6개의 다른 연료봉 모형을 기준으로 하여 TRIGA Mark-III 연구용 원자로의 핵특성이 자세히 분석되고 있다. 현재 핵연료로 사용하고 있는 FLIP fuel은 연료의 수명을 증진시키기 위해 개발되었던 모형이나, 70%의 고농축이기 때문에 비확산금지조약에 위배되어 수입이 곤란한 실정이다. 따라서 본 논문에서는 FLIP 연료 모형에 대치할 수 있는 다른 연료봉을 찾고 그들의 핵특성을 비교함으로써 앞으로 연료수입계획을 설립하고자 한다.

I. Introduction

TRIGA is a research reactor designed, manufactured and supplied by General Atomic Company in San Diego, California, U. S. A. The fuel is of rod-type consisting of uranium-zirconium-hydride clad either with alumium or stainless steel. Since 1958 this fuel has been adopted for use in nearly 50 reactors around the globe and has demonstrated considerable performance. In addition, several variations in fuel design have been developed to meet the variety of reactor use.

The Korean TRIGA Mark-II reactor is fuelled with 20 w/o enriched uranium, whereas TRIGA Mark-III reactor consists of mixed fuels, namely, 20 w/o enriched standard fuels and 70 w/o enriched FLIP (Fuel Lifefetime Improvement Program) fuels for the extension of fuel lifetime. The TRIGA Mark-II reactor fuel is clad with aluminum, while Mark-III reactor fuel is clad with stainless steel, and the latter is incorporated with erbium as burnable poison for the initial reactivity control.

In order to improve the proliferation resistance, the United States delegate made a proposal recently for the use of lower enriched fuel

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in research and test reactors[1].

It has been our perception that trade ban or supply reduction of highly enriched fuel elements for research reactors would certainly eliminate lower possible potential for being used as nuclear explosives. At the same time it would also eliminate or lower the current reactor utilization for research, training and isotope production, which are main functions of the reactors.

Similarly, the reduction of fuel enrichment by simple substitution for lower-enriched uranium in fuel design for the currently operating reactors would undoubtedly result in an immediate and direct effect upon reactor performance.

For the operational benefit of TRIGA Mark-III reactor, we set up the following criteria in evaluating fuel design:

a) Enrichment reduction should not cause unacceptable penalty in reactor performance.

b) Fuel cycle cost due to substitution for lower enriched fuel elements should remain within bearable boundary.

c) New fuel elements with lower enrichment and higher uranium desity should be as safe and reliable as ever.

The key technical note implied in the suggestion made by the U. S. delegates was to maintain the same U-235 density in the reduced enrichment design as in the currently utilized highly enriched fuel elements. This can be achieved by increasing uranium density in the fuel in proportion to the decrease in enrichment.

The purpose of this study is to examine the above constraints for the high and low enriched fuels in TRIGA Mark-III reactor currently operable in the Korea Atomic Energy Research Institute. The fuel models adopted in this study are:

1) Standard fuel (20 w/o enriched, 8.5 w/o uranium-loaded)

2) FLIP fuel (70 w/o enriched, 8.5 w/o uranium-loaded)

3) The proposed high density fuel (20 w/o enriched, 12 w/o uranium-loaded)

In addition to these fuel models, the following three types are also taken into consideration for verifying nuclear characteristics:

4) 40 w/o enriched, 8.5 w/o uranium-loaded fuel

5) 30 w/o enriched, 12 w/o uranium-loaded fuel

6) 20 w/o enriched, 20 w/o uranium-loaded fuel.

The reason for choosing the above cases is to see the intermediate behaviours of the fuel design which may compensate the disadvantages in the reactor performance due to enrichment reduction. According to General Atomic Company, they have not produced a higher uranium density fuel more than 12 w/o yet; however, such fuel could certainly be available if large amount of development cost would be invested for this task. Furthemore, analysis is carried out for case 6 in this paper on the ground that uranium-zirconium hydride fuels with 20 weight percent uranium loadings were already fabricated for the SNAP reactor project by Atomics International several years ago. Therefore, it is more than certain for thc fuel fabricator to produce TRIGA fuels with heavier uranium loadings to offset a forced lower enrichment.

At the same time, comparison of economics associated with the fuel models is made in terms of burnup with the assumption of purely sophisticated basis.

Some other questions with respect to safety-related areas such as potential for the positive void coefficient thereby resulting in negative effect in reactor safety aspect still remain unanswered. Uranium displaces some of hydrogen atoms and eventually reduces neutron moderation capability within the fuel although such is extremely important for negative temperature coeffi-

cients. This can be examined by comparing the negative temperature coefficients for the said two different fuel types: namely, FLIP fuel and the proposed 12 w/o uranium-loaded 20 w/o enriched high density fuel. Reactivity constraints are also analyzed in Chapter II.

In general, the core design must provide for neutron multplication constant substantially in excess of unity in order for the neutrons to permit subsequent compensation for fuel burnup, xenon and samarium effects and reactor power coefficient of reactivity.

As the result of our calculation and analysis, we have come to the conclusion that the Korean TRIGA Mark-III reactor will cost more than twice much with lower enriched and higher uranium-loaded proposed fuels than with the FLIP fuels which are 70 w/o enriched and 8.5 w/o uranium-loaded. On the other hand, discharge burnup with high density fuels turns out to be less than one sixth of that with FLIP fuels, although the former is more than 4 times of the standard fuels.

II. Analysis

The TRIGA Mark-III reactor installed at KAERI (Korea Atomic Energy Research Institute) has a circular grid pattern with hexagonal fuel elements, so that a simple way to identify core loadings is by reference to specific rings (A through G) in the core and the loadings within each ring (Fig. 1)

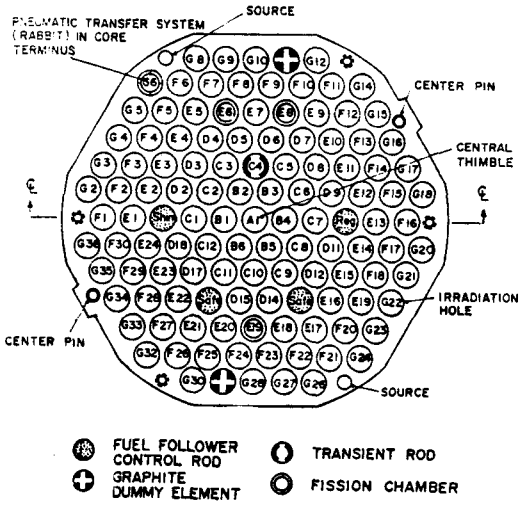

Fig. 1. Core Diagram.

The core contains 121 holes as follows:

108 fuel elements
4 fuel-follower control rods
1 central thimble, treated as water rod
1 transient control rod followed by void
3 fission chambers
1 pneumatic tube
1 irradiation hole.

Two of the holes are filled in with dummy elements for experiments in the core boundary. For the convenience'sake, three fission chambers and transient control rod are treated as void irradition holes. The analysis was initiated with 100 standard fuel elements. Then 12 more standard fuel elements are assumed to be fuelled into the core.

With burning a heterogeneous standard TRIGA core (many hexagonal elements of core material) to just critical and then burning further after incrementally replacing standard TRIGA fuels with FLIP or high density fuels starting with the B-ring and progressing radially outward until the entire core is to be composed of FLIP or higher uranium-loaded fuels.

The burnup model is based on actual operational history of KAERI reactor. For these calculations seven energy groups and 19×19 X-Y meshes are used. Seven groups are chosen so as to correspond to the basic cross-section input from General Atomic[2].

II. 1. Cell Calculation

An attempt is made in this section to examine the burnup characteristics of six different fuel types; namely, standard fuels (8.5 w/o uranium-

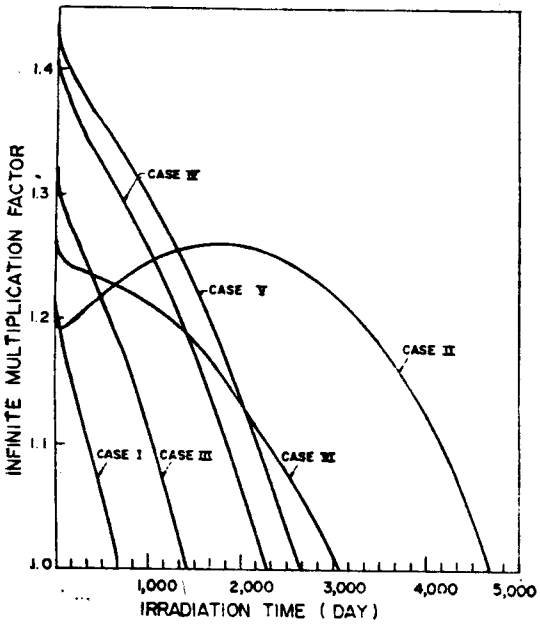

Fig. 2. K_∞ vs. Burnup for Fuel Cell

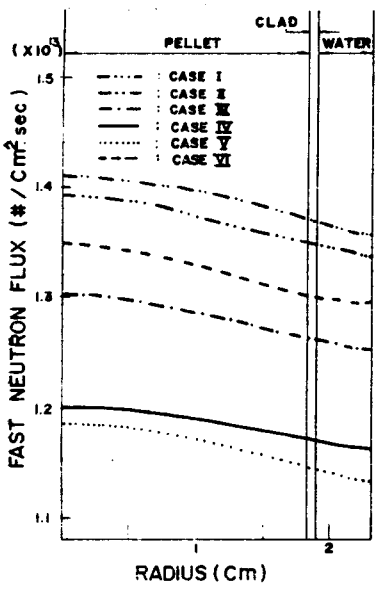

Fig. 3. Radial Fast Neutron Flux (Group 1) of Fuel Cell

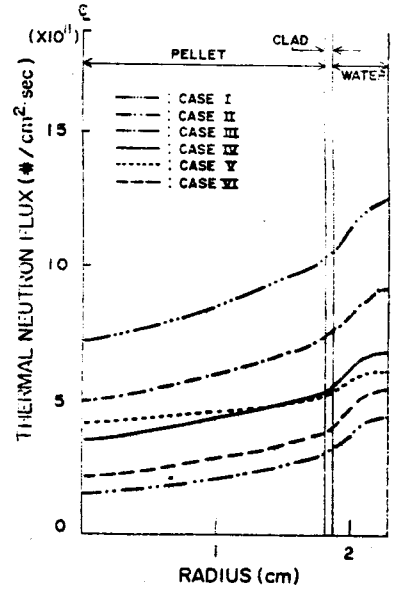

Fig. 4. Radial Thermal Neutron Flux (Group 7) of Fuel Cell.

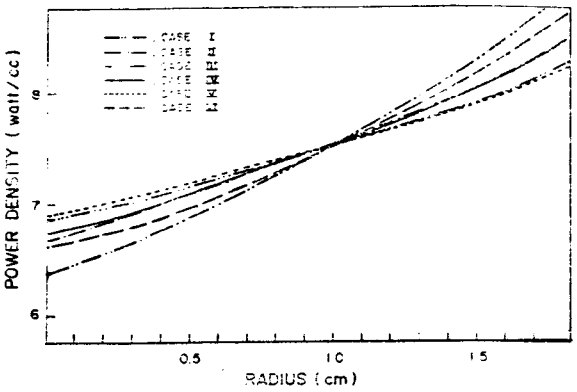

Fig. 5. Radial Power Distribution of Fuel Cell at BOL.

loaded with 20 w/o and 40 w/o enriched uranium), FLIP fuels (8.5 w/o uranium-loaded with 70 w/o enriched uranium) and highly uranium-loaded fuels (12 w/o uranium-loaded with 20 w/o and 30 w/o enriched uranium, and 20 w/o uranium-loaded with 20 w/o enriched uranium).

For this end, computation has taken place by means of seven group diffusion theory. To get rid of complication, the calculation ignores the existence of the slender zirconium rod at the centre of each fuel, which naturally causes slight neutron peaking, although such peaking is observable in the measured distrbuition[3]. This kind of analysis for the fuel cell also shows the neutron flux and power distribution inside the TRIGA fuel element as can be seen in Figs. 2

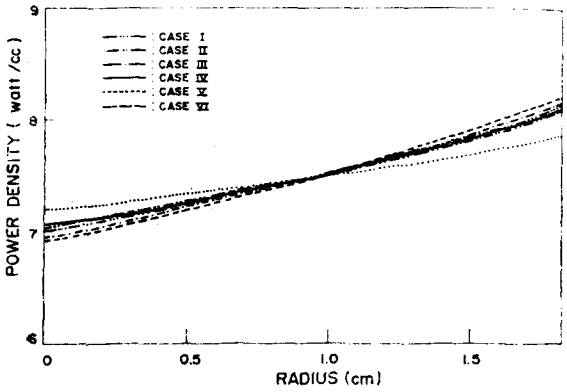

Fig. 6. Radial Power Distribution of Fuel Cell at EOL.

to 6. Needless to say, the knowledge of the neutron flux and power distribution may be an important factor in determining the safe operating limits of the fuel.

In order to provide maximum useful flux, the reactor design must push to maximum volumetric power density in the core. This is surely due to the fact that fast flux level in the core is the key utilization parameter, and fast flux density (nv) is proportional to volumetric power density. With more substitution of high density fuels, maximum fast flux cannot be achieved as shown in Fig. 3.

The flux depression factor, which is defined as the ratio of the averaged flux of fuel region to that of surface, is calcuated for six fuel types as shown in Table 1. Since this factor largely depends on the neutron absorption and its mean free path, the flux depression factor is greater than one, that is, the averaged flux in fuel region is greater than one in fast energy group, while this factor is below one and decreases with burnup in thermal energy range. And, among six fuel types, the flux depression for the FLIP fuel which has more U-235 with large absorption cross-section than other fuel types, is highest in the thermal energy gruop.

II. 2. Burnup Analysis

To refuel the KAERI's Mark-III reactor, FLIP fuel is chosen to be reloaded after the first full standard fuel core, The original plan called for the reloading of FLIP fuels taking place in a couple of time steps, but concrete schedule for the future fuelling programme has not yet been drawn up. For the calculational convenience, nine time steps are chosen so as to correspond to the refuelling steps as follows:

1 time step each for B through D rings

2 time steps for E through G rings.

Table 2 explains these time steps in details.

This plan is revised to replace FLIP fuels with highly uranium loaded fuels in order to improve the possibility of proliferation resistance. KAERI reactor had experienced the first full-core stage with standard fuels in 1975, and now the mixed core contains 19 FLIP elements and 95 standaid elements. So our model for this burnup calculation is set forth as follows:

1) The mixed core begins at the first full-core with standard fuel elements only

2) Refuelling time is set when excess reactivity becomes null

3) Discharge burnup is determined as the B-ring fuel elements are refuelled again

4) In all of the calculations, the four control rods and a transient rod are assumed to be completely withdrawn; thus the poison sections are replaced by fuel elements (if the rod has a

Table 1. Flux Depression Factor (BOL)

Energy group	1	2	3	4	5	6	7
Case I 8.5w/o-20%	1.02	1.01	0.99	0.99	1.04	0.97	0.83
Case II 8.5w/o-70%	1.02	1.01	0.99	0.96	0.96	0.85	0.71
Case III 12w/o-20%	1.01	1.01	0.99	0.99	0.92	0.93	0.87
Case IV 8.5w/o-40%	1.01	1.01	0.99	0.99	1.01	0.93	0.84
Case V 12w/o-30%	1.01	1.01	0.98	0.98	1.01	0.92	0.91
Case VI 20w/o-20%	1.01	1.01	0.99	0.98	1.01	0.90	0.79

Table 1-1. Flux Depression Factor (EOL)

Energy group	1	2	3	4	5	6	7
Case I 8.5w/o-20%	1.02	1.01	1.00	0.99	1.05	0.98	0.86
Case II 8.5w/o-70%	1.02	1.01	0.99	0.96	0.99	0.88	0.76
Case III 12w/o-20%	1.01	1.02	1.02	0.88	1.02	0.97	0.90
Case IV 8.5w/o-40%	1.01	1.01	0.99	0.99	1.03	0.97	0.91
Case V 12w/o-30%	1.01	1.01	0.98	0.98	1.04	0.96	0.95
Case VI 20w/o-20%	1.01	1.01	0.99	0.99	1.04	0.95	0.86

Table 2. Refuelling Mode of TRIGA Mark-III Reactor

Refuelling Sequence	Number of Fuels	Ring Number
1	6	B—1, 2, 3, 4, 5, 6
2	11	C—1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
3	18	D—1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18
4	9	E—2, 5, 7, 9, 12, 15, 18, 20, 23
5	12	E—1, 3, 4, 10, 11, 13, 14, 16, 17, 21, 22, 24
6	15	F—2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 25, 26. 28. 30
7	15	F—1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29
8	15	G—4, 5, 8, 9, 16, 17, 18, 21, 22, 27, 30, 32, 33, 34
9	11	G—2, 3, 10, 12, 14, 15, 23, 24, 26, 28, 35, 36

fuel-follower) and a void (for the void-follower rod).

Basic input data, such as cross-sections, number densities, uranium loadings, basic cell data, fission spectrum and axial bucklings for the first three cases, were obtained from General Atomic Company, and all such data are said to have been verified by experimental data. For the assumed fuel types, group constants were generated by GAM-THERMOS and utilized in this analysis. Dimensions of each region and volume fractions of the various components in each region are determined for the KAERI's TRIGA reactor core. The preparation of input data for CITATION from the data furnished by General Atomic is accomplished by another program written for this purpose. All the technical data for six fuel types are provided in Appendix.

II. 3. Temperature Coefficients

A common requirement in research and test reactor design calls for sufficiently large prompt negative temperature coefficient of reactivity so that when integrated to the fuel melting temperature it tends to become more than adequate to compensate for credible accidental reactivity insertions. In low-enrichment reactors, an adequate temperature coefficient is available from the Doppler-broadening of resonance peaks in the absorption cross-section of U-238 and the concomitant increased neutron absorption. As enrichment increases to 93%, no singnificant Doppler effect exists. U-ZrH fuels have substantial Doppler effect when loaded with low-enrichment fuels.

In order to permit the pulse mode operation in TRIGA Mark-III reactor, a given fuel design must be incorporated with a large negative temperature coefficient of reactivity. This negative effect provides an inherent prompt shutdown mechanism for the reactor during rapid power rise.

The presence of a large fraction (about half) of the hydrogen moderator in the fuel provides another source of substantial negative temperature coefficient of reactivity from the prompt shift in thermal neutron when the fuel is heated up. The neutron spectrum shifts to higher energy, where increased leakage and increased absorption when a resonance burnable-poison is present, causes a reactivity loss. Displacement of ZrH by U in the TRIGA fuel element, say, to increase uranium weight fraction to compensate for enrichment limits, decreases the fraction of moderator within the TRIGA fuel and, therefore, reduces this source of negative temperature coefficient,

The TRIGA core design does not lend itself to simple variations of the core size, lattice arrangement or fuel design because;

1) Displacement of the $ZrH_{1.6}$ to add uranium of lower enrichment will reduce the prompt negative temperature coefficient and also reduce the fuel heat capacity (U has 1/3 the heat capacity of ZrH),

2) Larger core diameters will gain reactivity required to compensate for lower enrichment, but this may tend to cause a positive temperature coefficient of reactivity,

3) The potential of a positive temperature coefficient also limits the lattice spacing and, since the lattice is already spaced tightly to avoid a positive coefficient, the possibility of any tighter spacing by increasing fuel rod diameters is essentially excluded due to the thermal hydraulic requirements.

Analysis in this study is limited to TRIGA Mark-III core to compare the effect of temperature coefficient of two fuel types FLIP fuels and the proposed 12 w/o uranium-loaded fuel with 20 w/o enriched. Basic group cross-sections are regenerated by GAM-THEROS which correspond to fuel tempratures of 23°C, 200°C and 400°C. These group constants are utilized in TRIGA core to evaluate the reactivity changes. The results are shown in Table 3. Based on this analysis, high-density-fuel-loaded-core has smaller negative temperature coefficient than FLIP-loaded core by about a half. This may not affect the safety restraint because of the opposite effect due to Doppler broadening.

II. 4. Results of the Calculation

Refuelling by the lumped addition up to 18 new fuel elements to the core provides additional amount of core life and additional reactivity after xenon buildup. These results are displayed graphically in Figs. 7 through 12.

Table 3. Temperature Coefficient

Fuel	Temperature Coefficient ($\Delta k/k°C$)
High Density (12 w/o-20%)	-8.927×10^{-5}
FLIP (8.5 w/o-70%)	-1.486×10^{-4}

The calculation is made for operating temperatures and includes the reactivity loss associated with 2 MW equilibrium xenon. Hence Figs. 7 through 12 represent available excess reactivity at 2 MW. Refuelling began with the six B-ring

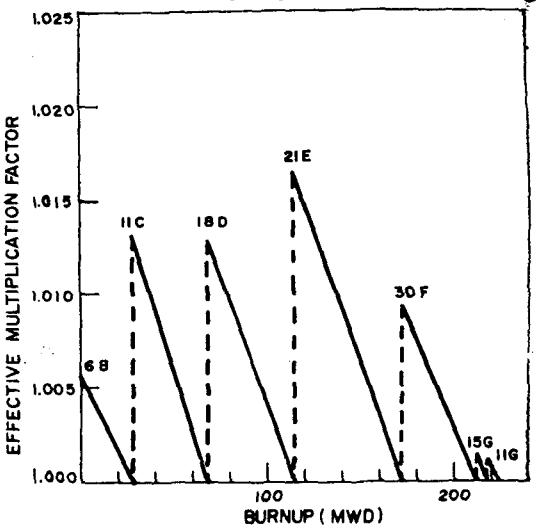

Fig. 7. Reactivity History of Standard Fuel Core.

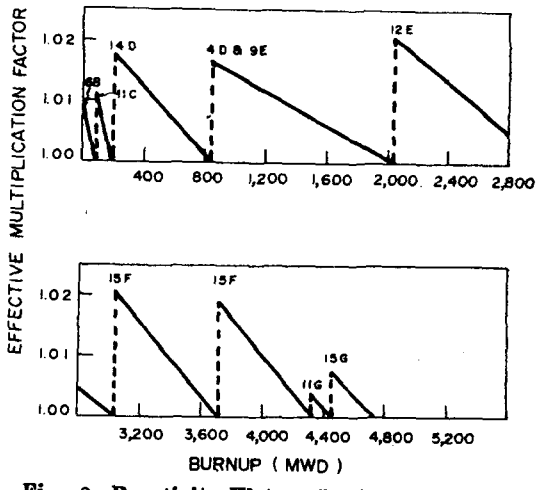

Fig. 8. Reactivity History During Conversion to Flip Fuel.

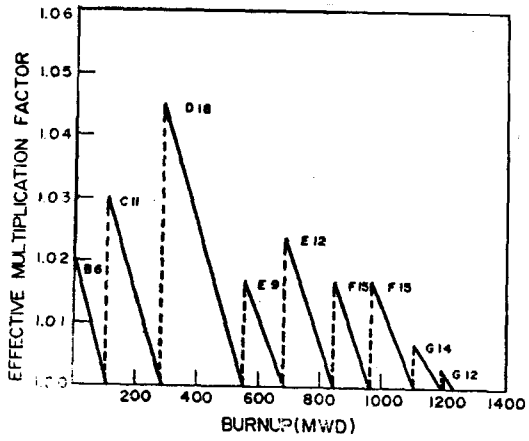

Fig. 9. Reactivity History During Conversion to High Density (12 w/o-20%) Fuel.

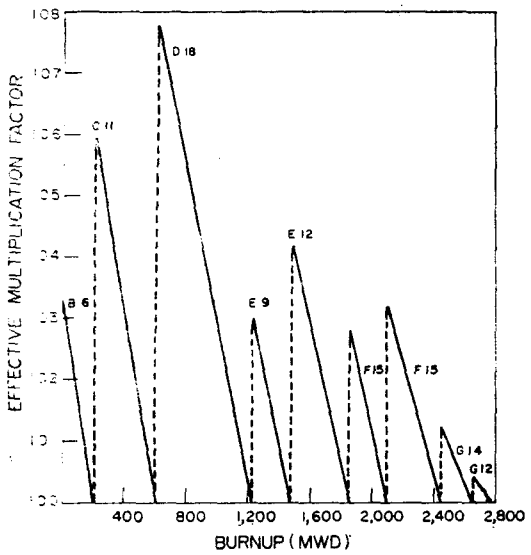

Fig. 10. Reactivity History During Conversion to Case IV (8.5 w/o-40%) Fuel.

elements and progressed radially outward until entire core has been loaded with new fuel elements. No fuel shuffling was attempted at all. The FLIP fuel elements or high density fuel elements simply replaced the burned standard elements which were loaded in the core. Fig. 8 shows very clealy the increase in core life when refuelled with FLIP fuels. Life of the FLIP core stretches to around 4,730 MWD, whereas that of the high density fuel core 1,234 MWD.

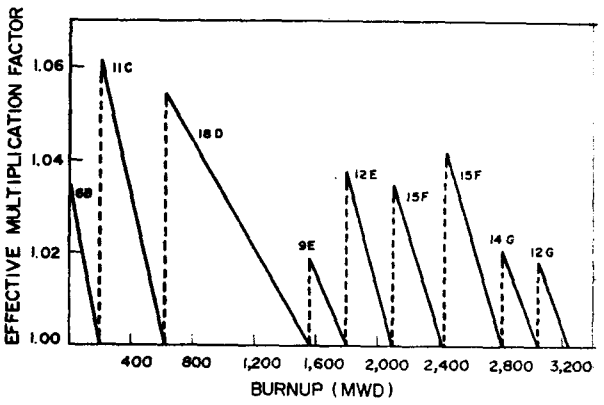

Fig. 11. Reactivity History During Conversion Case V (12 w/o-30%) Fuel.

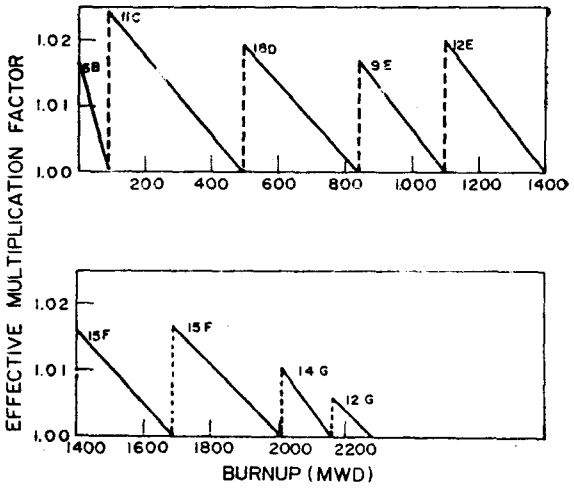

Fig. 12. Reactivity History During Conversion to Case VI (20 w/o-20%) Fuel.

Compared to the analysis of General Atomic's[4] 126-position G-ring core with FLIP fuel elements, starting with 90 standard elements, the stretched burnup is lower by about 2,000 MWD. This occurs because our core is smaller and consists of 112 fuel elements. Also this was caused by 2 MW operation for the whole analysis. One can also determine from Figs. 7 to 12 the excess reactivity at any stage of burnup for the various core compositions.

It is observed for B and C-ring refuelling that high density fuel has larger excess reactivity than that of FLIP. This mainly occurs because

FLIP elements in a standard TRIGA core see the softer neutron spectrum characteristics of the standard TRIGA core than high density uranium-loaded fuel elements. The FLIP elements, therefore, burn up slightly faster than they had been loaded with high density fuel with its harder spectrum. Further additional refuelling turns this phenomenon over so as to burn high density core more rapidly as depicted in Figs. 8 and 9 due to spectrum softening. The radial neutron flux distributions at the first refuelling stage and after G-2 refuelling (Figs. 13 through 24) are illustrated for the representation of central line of the core. In order to examine the criterion that enrichment reductions must not cause unacceptable reactor performance decreases, power-per-unit-flux for each case fuel is depicted in Figs. 25 and 26. Our analysis indicates that FLIP fuel has higher power-per-unit-flux especially for thermal flux.

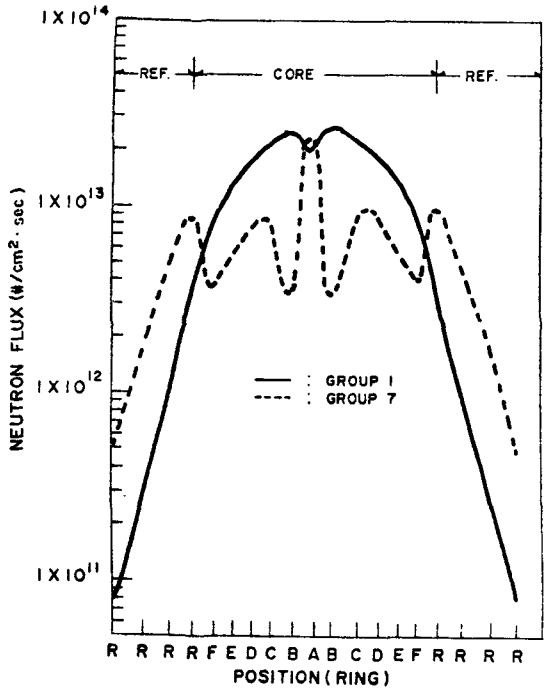

Fig. 13. Radial Neutron Flux Distribution of Core Refuled With Standard Fuel in B-Ring.

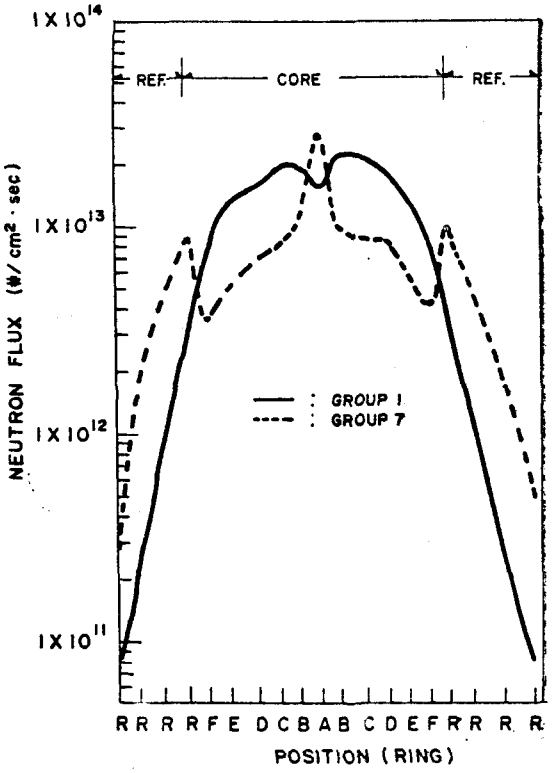

Fig. 14. Radial Neutron Flux Distribution of Standard Fuel Core at Discharge.

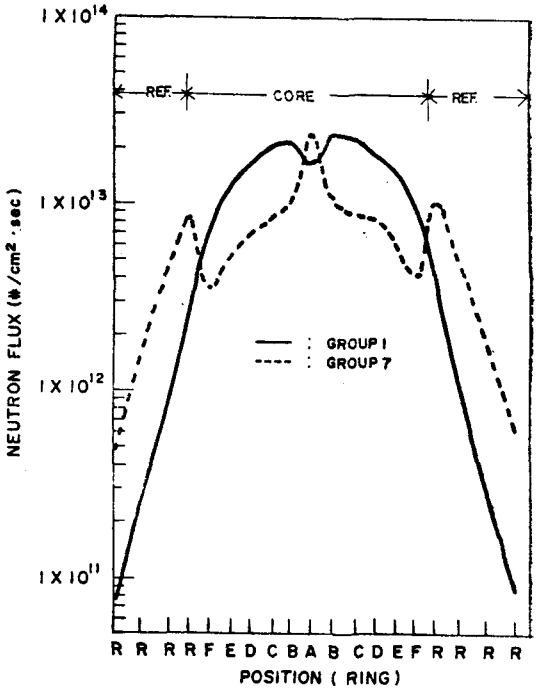

Fig. 15. Radial Neutron Flux Distribution of Core Refueled with FLIP Fuel in B-Ring.

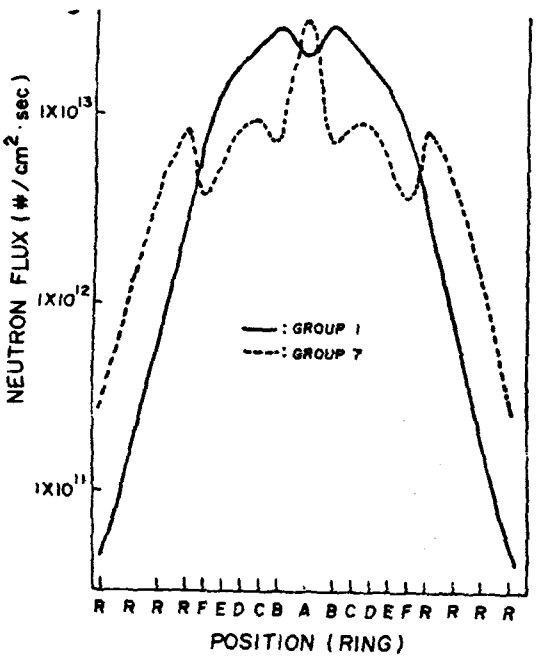

Fig. 16. Radial Neutron Flux Distribution of FLIP Fuel Core at Discharge.

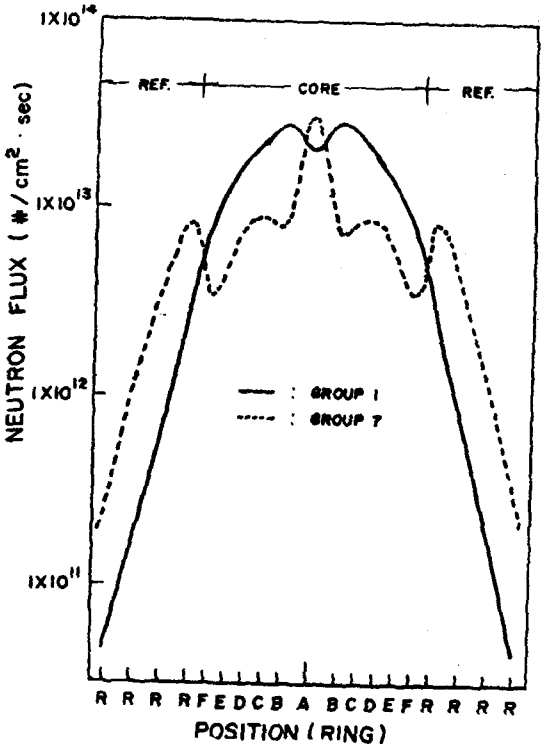

Fig. 17. Radial Neutron Flux Distribution of Core Refueled with High Density (12 w/o-20 %) Fuel in B-Ring.

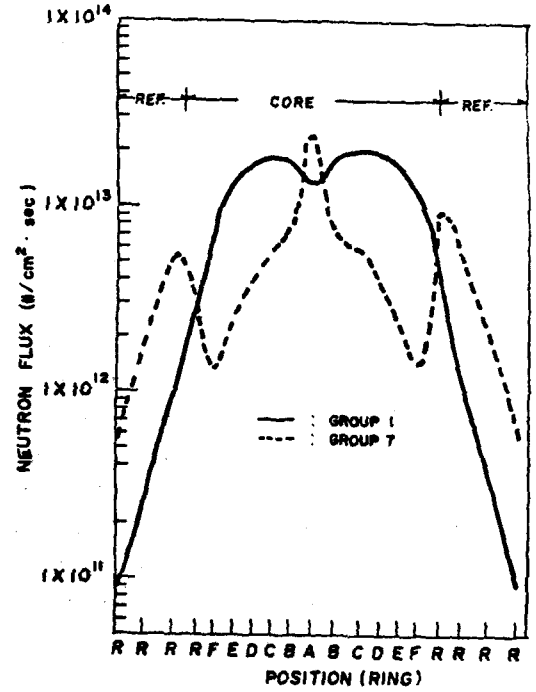

Fig. 18. Radial Neutron Flux Distribution of High Density (12 w/o-20%) Fuel Core at Discharge.

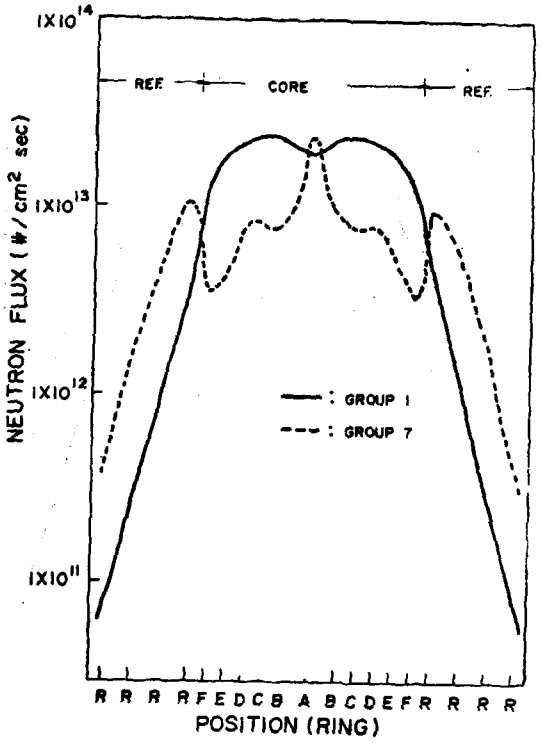

Fig. 19. Radial Neutron Flux Distribution of Core Refueled with IV (8.5 w/o-40 %) Fuel in B-Ring.

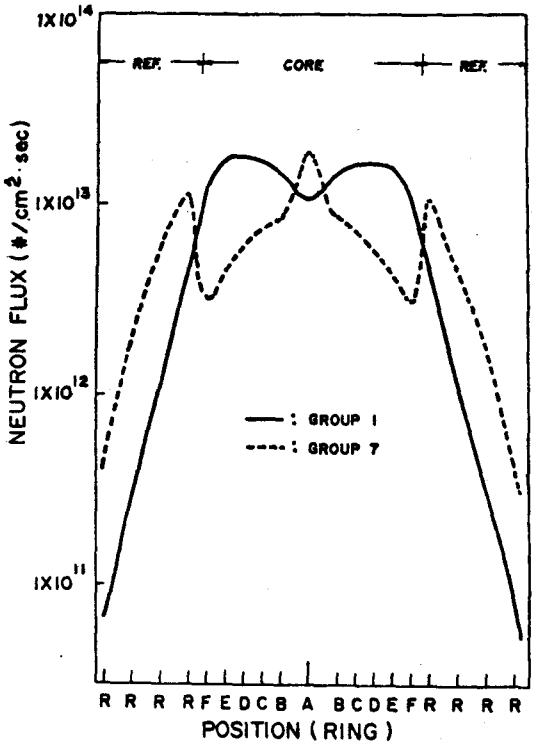

Fig. 20. Radial Neutron Flux Distribution of Case IV (8.5w/o-40%) Fuel Core at Discharge.

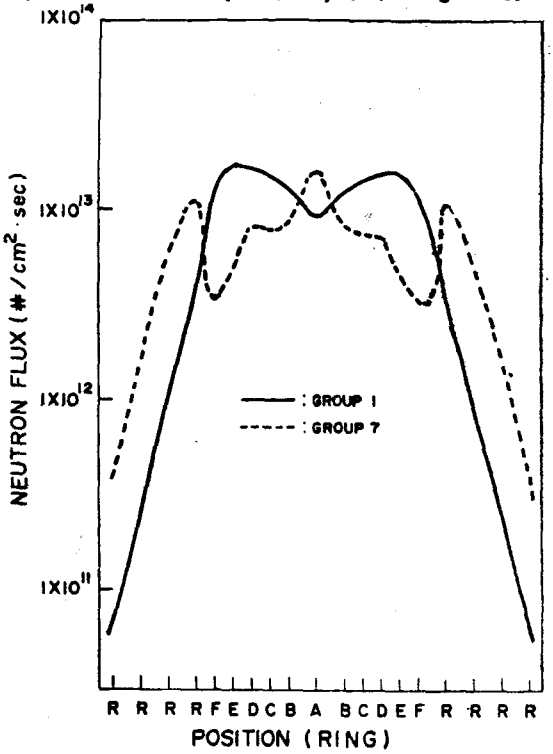

Fig. 21. Radial Neutron Flux Distribution of Core Refueled with Case V (12 w/o-30%) Fuel in B-Ring.

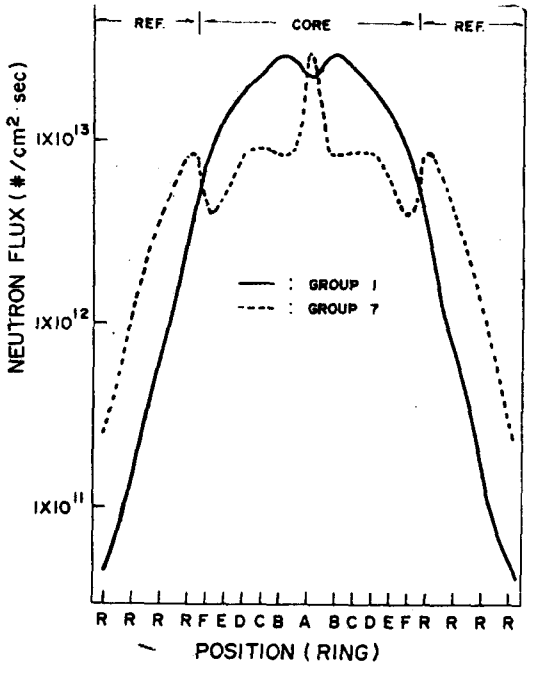

Fig. 22. Radial Neutron Flux Distribution of Case V (I2 w/o-30%) Fuel Core at Dischrge.

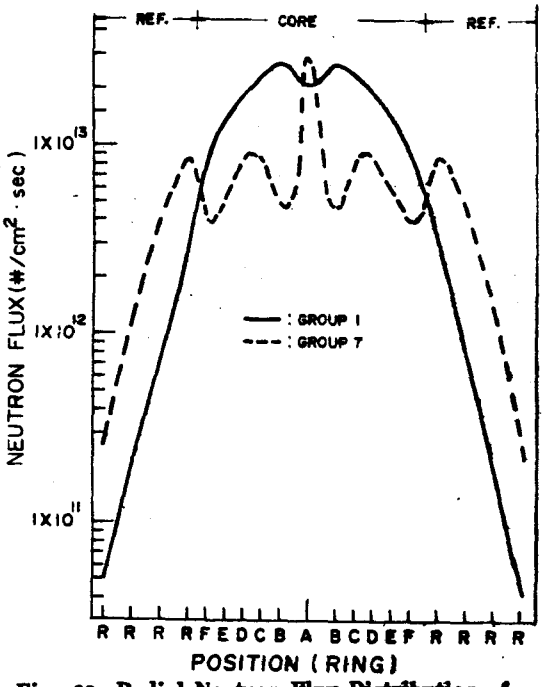

Fig. 23. Radial Neutron Flux Distribution of Core Refueled with Case VI (20 w/o-20%) Fuel in B-Ring.

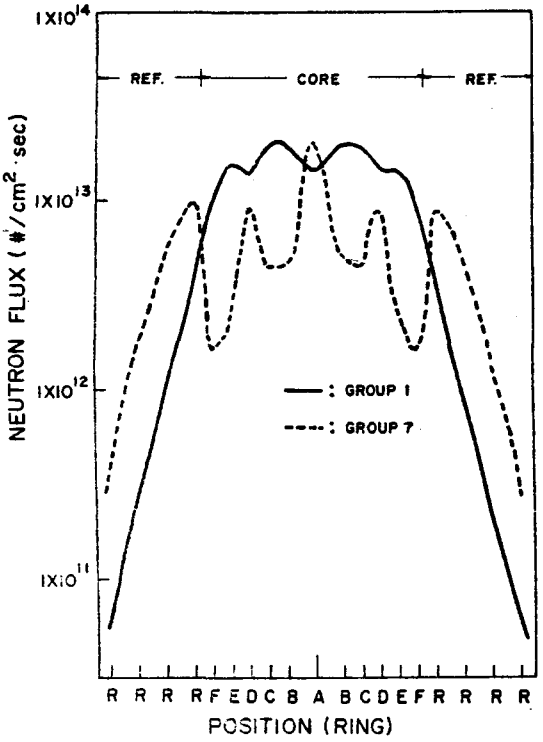

Fig. 24. Radial Neutron Flux Distribution of Case VI (20 w/o-20%) Fuel Core at Discharge.

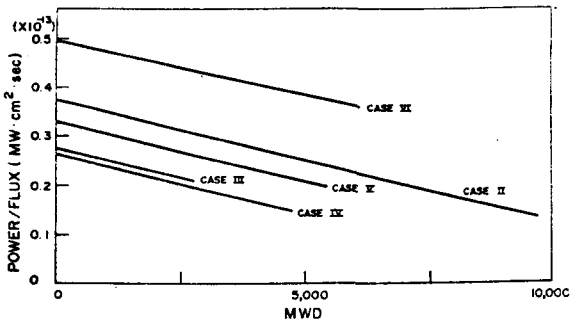

Fig. 25. Power-per-unit-flux for Fast Group

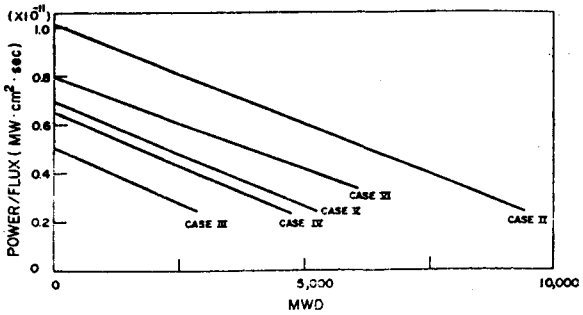

Fig. 26. Power-per-unit-flux for Thermal Group

III. Cost Analysis

Based on the current fuel price quotation, cost analysis is carried out for the core burnup with the condition of incremental refuelling and average discharge burnup. Assumption is made for the discharge burnup of B-ring fuel at the end of life after the core has been fully loaded with 112 fresh fuel elements. Table 4 shows the current price of TRIGA fuels. Fabrication costs for Cases I, II, III and VI fuels are quoted from the current price of General Atomic Co[5]. and costs for other fuels are estimated by uranium density. Based on the current price of uranium ore ($115/kg U) including the conversion and enrichment service charge ($86.65/kg SWU), the price of 70 w/o enriched uranium is estimated as $31,160/kg and that of 20 w/o enriched uranium is $8,511/kg. According to our experience the delivery charge including crating and air freight is about $100 per element. The total fuel price of standard fuels turns out to be $4,514 per element, and that of FLIP fuels, being the most expensive fuel element, is 2.2 times the standard fuel.

III. 1. Incremental Refuelling

In the case of incremental refuelling with new fuel elements, initially loaded with 112 fuel elements (8.5 w/o, 20% enriched) in the KAERI's TRIGA Mark-III reactor, the core burnup estimations are shown in Table 5. The core burnup of each case (case II to case VI) is 21, 6, 12, 15 and 10 times the case I fuels in ascending order.

Table 4. Price of Fuel Element

	Case I 8.5 w/o-20%	Case II 3.5 w/o-70%	Case III 12 w/o-20%	Case IV 8.5 w/o-40%	Case V 12 w/o-30%	Case VI 20 w/o-20%
Uranium Quantity(kg)	0.1955	0.1955	0.2830	0.1955	0.2830	0.5141
U235 Quantity(kg)	0.0391	0.1369	0.0566	0.0782	0.0849	0.1028
Fabrication ($/element)	2,750	3,650	3,100	2,750	3,100	3,650
Uranium ($/element)	1,664	6,092	2,409	3,426	3,681	4,376
Delivery ($/element)	100	100	100	100	100	100
Table ($/element)	4,514	9,842	5,609	6,276	6,881	8,126

*1. Uranium Ore=$115/kg U including Conversion
2. Enrichment Service=$86.65/kg SWU

Table 5. Core Burnup and Fuel Cost at Incremental Refuelling (112 elements)

	Case I 8.5 w/o-20%	Case II 8.5 w/o-20%	Case III 12 w/o-20%	Case IV 8.5 w/o-40%	Case V 12 w/o-30%	Case VI 20 w/o-20%
Core Burnup (MWD)	224	4,730	1,234	2,780	3,320	2,250
Total Fuel Cost* ($)	505,568	1,102,304	628,208	702,912	770,672	910,112
Unit Fuel Cost ($/MWD)	2,257	233	605	253	232	404

*: $/element x 112 elements

The unit costs calcutated for each case are also shown in Table 5. The unit costs of case II and case V are turned out to be very close and most inexpensive among all cases. The unit costs of case IV are slightly higher compared with case II or case V, but much cheaper than the others. The unit costs of case II or case V are about 1/10 of case I and about a half of case III or case VI.

III. 2. Discharge Burnup

The discharge burnup, i.e., the burnup of B-ring fuel with the condition of full refuelling, estimated for each case is depicted in Table 6. The unit fuel costs at this discharge burnup are about a half of those of incremental refuelling, because the power ratio of B-ring fuels to the core average is nearly 2. And the details of the unit fuel costs at this discharge burnup are similar to those of incremental refuelling.

It has been common practice in the Korea Atomic Energy Research Institute that TRIGA Mark-III reactor is operated for 50 hours per week and 48 weeks a year mainly for the purpose of radioisotope production and various experiments. Under this operational mode, annual power generation results in 200 MWD, and the approximate number of annual fuel requirement is 60, 3, 11, 5, 4 and 6 elements for each case in ascending order.

On the other hand, the details of annual financing requirement for each case is similar to the unit fuel costs also.

Annual uranium ore and enrichment service requirements for case II, case V and case IV are similar and about 1/5 those of case I. And those of case III or case VI are about 1/4 those of case I.

All of these shows that case I, case III and case IV fuels which are all 20 w/o enriched uranium fuels, are expensive compared with other cases which are enriched more than 20 w/o U-235. Among 20 w/o enriched uranium

Table 6. Discharge Burnup and Annual Fuel Repuirement

	Case I 8.5 w/o-20%	Case II 8.5 w/o-70%	Case III 12 w/o-20%	Case IV 8.5 w/o-40%	Case V 12 w/o-30%	Case VI 20 w/o-20%
1. Discharge Burnup						
(MWD/MTU)	17,187	393,299	65,583	218,363	177,103	69,422
(MWD/element)	3.36	76.89	18.56	42.69	50.12	35.69
Unit Fuel Cost* ($/MWD)	1,343	128	302	147	137	228
2. Annual Fuel Requirement Power Generation						
(MWD/annum)	200	200	200	200	200	200
Fuel Requirement (elements/annum)	60	3	11	5	4	6
Financing Requirement ($/annum)	270,840	29,526	61,699	31,380	27,524	48,756
U_3O_8 Requirement* (lb/element)	20.0	69.3	28.5	48.4	42.8	51.32
(lb/annum)	1203.3	208.0	313.5	242.1	171.3	308.0
Enrichment Service Requirement*						
(SWU/element)	8.9	34.1	13.0	18.9	20.1	23.5
(SWU/annum)	536.7	102.3	143.0	94.4	80.4	141.2

*: 0.2 w/o Tails Assay

fuels, case I fuel is most expensive and is more than 4 times others. Therefore, penalty attributed to using the case I fuels in TRIGA Mark-III reactor is significant not only from the viewpoint of economics but also from the resources utilization aspects. Futhermore, frequent refuelling with 20 w/o enriched uranium fuels cannot but make the reactor utilization rate lower than those with higher enriched fuels.

IV. Discussions

The immediate effect of reducing reactor performance caused by lower enriched fuel loading should be carefully examined. According to our analysis, mere substitution of the proposed high density (12 w/o uranium-loaded) fuels costs at least twice more than relying on FLIP fuels and significantly reduces the flux performance as well. This is shown in Figs. 3 and 4 that flux level produced in the core by FLIP fuels is much higher than the level produced by high density fuels.

Also there are still some questions to be answered with respect to safety-related areas. In the case of TRIGA fuels, the prompt negative temperature coefficient is the basic characteristic which determines the core behaviour during pulse operation. The presence of a large fraction of the hydrogen moderator in the TRIGA-fuel produces a source of substantial negative temperature coefficient of reactivity from the prompt shift in thermal neutron spectrum when the uranium hydride fuel is heated. The rise in temperature of the hydride increases the probability that a thermal neutron in the fuel element will gain energy from an oscillating hydrogen atom of excited states in the lattice. As the neutrons gain energy from the ZrH, their mean free path increases appreciably. Since the average chord length in the fuel element is comparable with a mean free path, the proba-

bility of neutron escape from the fuel element before capture increases. Nevertheless, the analysis shows that the use of high density fuels does not violate the safety limits.

In water the neutrons are rapidly re-thermalized so that the capture and escape probabilities are relatively insensitive to energy with which the neutron enters into water. The heating of the moderator mixed with the fuel thus causes the spectrum to harden more in the fuel than in water. As a result, there is a temperature dependent disavantage factor for the unit cell in the core which decreases the ratio of absorptions in the fuel to total-cell absorptions as the fuel element temperature increases. This brings about a shift in the core neutron balance giving a loss of reactivity. Therefore, displacement of ZrH by uranium in the highr-uranium loaded fuel (12 weight %) decreases the fraction of moderator within the TRIGA fuel to reduce the source of negative temperature coefficient. This could be balanced by Doppler broadening effect in large fraction of U-238. However, this should be carefully examined.

The refuelling scheme is set up in this analysis so that reactivity values corresponding to K_{eff} values for each cycle are not beyond about 1. This value is chosen because the large amount of reactivity is a safety hazard requiring many control rods and/or large amounts of burnable poison and because metallurgical burnup limits are reached while the fuel is still highly reactive.

Our analysis shows that 20 w/o uranium-loaded fuel may be theoretically substituted for the FLIP fuel without reducing the reactor performance. However, this fuel type has not been commercially proven yet.

A very little attention has been devoted to the report on details and values of the power peaking at various stages of burnup. Tables 7 though 9, however, should be useful as a summary of maximum peak-to-average power valus at each stage of burnup. In reality, this high peak cannot happen because irradiation samples are usually inserted in water-filled central thimble.

Table 7. Power Peaking Ratio in Standard Core

No.	Refuelling Step	Peaking Position	Peaking Power Ratio
1	B Ring	B6	1.8439
2	C Ring	B6	1.7763
3	D Ring	B2	1.7118
4	E Ring	B6	1.6494
5	F Ring	B6	1.5979
6	G-1 Ring	B6	1.5977
7	G-2 Ring	B6	1.5894

Table 8. Power Peaking Ratio in FLIP Core

No.	Refuelling Step	Peaking Position	Peaking Power Ratio
1	B Ring	B6	2.2218
2	C Ring	B6	1.9327
3	D Ring	B2	1.9342
4	E-1 Ring	B6	2.0357
5	E-3 Ring	B6	2.0560
6	F-1 Ring	B2	1.8080
7	F-2 Ring	B2	1,5466
8	G-1 Ring	C12	1.3977
9	G-2 Ring	C12	1.3098

Table 9. Power Peaking Ratio in High Density (12 w/o-20%) Core

No.	Refuelling Step	Peaking Position	Peaking Power Ratio
1	B Ring	B6	2.1850
2	C Ring	B6	1.9608
3	D Ring	B6	1.7934
4	E-1 Ring	B6	1.6870
5	E-2 Ring	B6	1.5742
6	F-1 Ring	B6	1.4779
7	F-2 Ring	D17	1.3679
8	G-1 Ring	D17	1.3273
9	G-2 Ring	D18	1.2961

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2. G.B. West, Private Communication, General Atomic Co., March 1978.
3. J.D. Randall, D. Schauer and J. Taft, "Determination of the Radial Power Distribution in a TRIGA FLIP Element, TOC-7, Fourth Biennial TRIGA Reactor Owner's Conference, Salt Lake City," March 1976.
4. M.P. Naughton and G.B. West, "Study of Improved Lifetime Resulting from the Incremental Addition of FLIP Fuel to Standard TRIGA Core", GA-10293, September 1970.
5. R. Peters, Private Communication, General Atomic Co., August 15, 1978.

APPENDIX
Technical Data for TRIGA Mark-III Fuels

Table A.1. Atomic Density of Fuel Cell

Region \ Fuel Type		8.5U (20)-ZrH Fuel Element		8.5U (70)-ZrH Fuel Element		12U (20)-ZrH Fuel Element	
		Cell Atomic Densities (10^{24}nuc./cc)	Homogenized Atomic Densities (10^{24}nuc./cc)	Cell Atomic Densities (10^{24}nuc./cc)	Homogenized Atomic Densities (10^{24}nuc./cc)	Cell Atomic Densities (10^{24}nuc./cc)	Homogenized Atomic Densities (10^{24}nuc./cc)
Fuel-Moderator	H(ZrH)	0.056678	0.036030	0.054992	0.034958	0.055977	0.035585
	Zr	0.035626	0.022647	0.035645	0.022660	0.035212	0.022384
	U-235	0.000252	0.000160	0.000883	0.000561	0.000366	0.000232
	U-238	0.000995	0.000633	0.000373	0.000237	0.001444	0.000918
	Er-167	—	—	0.0000755	0.000048	—	—
Cladding	SS	0.0843	0.003026	0.0843	0.003026	0.0843	0.003026
Water	$H(H_2O)$	0.0668	0.021937	0.0668	0.021937	0.0668	0.021937
	O	0.0034	0.010968	0.0334	0.010968	0.0334	0.010968

Continued

Table A.1. Atomic Density of Fuel Cell

Region \ Fuel type		8.5U(40)-ZrH Fuel Element		12U(30)-ZrH Fuel Element		20U(20)-ZrH Fuel Element	
		Cell Atomic Densities (10^{24}nuc./cc)	Homogenized Atomic Densities (10^{24}nuc./cc)	Cell Atomic Densities (10^{24}nuc./cc)	Homogenized Atomic Densities (10^{24}nuc./cc)	Cell Atomic Densities (10^{24}nuc./cc)	Homogenized Atomic Densities (10^{24}nuc./cc)
Fuel-Moderator	H(ZrH)	0.056678	0.036030	0.055977	0.035585	0.054510	0.034652
	Zr	0.035626	0.022647	0.035212	0.022384	0.034069	0.021658
	U-235	0.000504	0.00032039	0.000549	0.000345	0.0006559	0.00041696
	U-238	0.000746	0.00047423	0.0012635	0.00080321	0.0026237	0.0016679
	Er-167	—	—	—	—	0.00002389	0.000015187
Cladding	SS	0.0843	0.003026	0.0843	0.003026	0.0843	0.003026
Water	$H(H_2O)$	0.0668	0.021937	0.0668	0.021937	0.0668	0.021937
	O	0.0334	0.010968	0.0334	0.010968	0.0334	0.010968

Table A. 2. Fuel Cell Dimension

Cell region	Radius		Area	Volume	volume Frac-tion
	in.	cm	cm^2	cm^3	
U-ZrH	0.7175	1.822	10.434	397.54	0.6357
Stainless Steel Clad	0.7375	1.873	0.590	22.48	0.0359
Water	0.9000	2.286	5.390	205.36	0.3284
Total Cell			16.414	625.38	1.0000

Table A. 3. Energy Group Structures used for TRIGA Reactor Nuclear Analysis Calculations

Group	Energy Range		
	Fast Groups	Thermal Groups	
		Cell Calculation	Reactor Calculation
		(eV)	(eV)
1	15MeV-0.603MeV	1.125-0.75	1.125-0.42
2	603KeV-9.12KeV	0.75-0.57	0.42-0.14
3	9.12KeV-1.125-eV	0.57-0.42	0.14-0.05
4		0.42-0.26	0.05-0.002
5		0.36-0.14	
6		0.14-0.05	
7		0.05-002	

Table A. 4. Fission Spectrum and Buckling Factor

Group	Fission Spectrum	Buckling Factor	
		Standard Core	FLIP
1	0.83	0.0041	0.00555
2	0.17	0.0041	0.00456
3	0.0	0.0041	0.00360
4	0.0	0.0041	−0.00022
5	0.0	0.0041	0.00617
6	0.0	0.0041	−0.01905
7	0.0	0.0041	−0.0827

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