A Search into the Optimal U-Pu-Th Fuel Cycle Options for the Next Millennium

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ABSTRACT

Early induction of thorium in a reactor using enriched uranium seed was proposed earlier[1]. The new reactor concept, though in a stage of inception, was found to have many attractive features. In the equilibrium core, 50% of the core loading could be thorium with no external feed enrichment. Low excess reactivity and power distributions with adequate thermal margins could be intrinsically maintained for a fuel cycle duration of an year or more by judicious uranium and thorium loading. No conventional absorber control maneuver was needed for operation at full power. Though the reactor considered pressure tube type design with segregated coolant and moderator, negative or near zero void coefficient could be achieved by proper design of the fuel assembly. The reactor was adjudged to be inherently safe since reactivity based transients were either absent or less probable. In the present work, two types of seed materials, viz., Pu or ^{233}U in thorium, are studied in addition to enriched uranium. All the core characteristics stated above, are seen to be preserved in the core designs with different seed materials.

1. INTRODUCTION

The nuclear thermal power reactors, world over, use natural or enriched uranium as fuel. Though thorium is an equal candidate for nuclear power, it is not yet preferred one for commercial reasons. When the naturally available fissile isotope, ^{235}U, will be nearly exhausted, use of thorium would be feasible only with the help of the other man-made fissile material, viz. plutonium. The cost thereof would however be far too high in comparison to the fuel cycle costs of the present day power reactors. Thus the relatively low fuel cost of the present (U-Pu) fuel cycle is achieved essentially by a conscious indifference to the mounting burden on future power reactors that would employ reprocessed plutonium with depleted uranium or thorium. In our earlier study, it was emphasized that thorium should be burnt along with uranium. Induction of thorium in a major way in a reactor using enriched uranium fuel was described[1-3]. In this concept a segregated loading of thorium and uranium is considered. Some core concepts had been suggested for production of ^{233}U in commercial power reactors[4]. The unique feature of our concept is that thorium needs no external feed enrichment. The insitu formation of ^{233}U in the same reactor is found to be adequate, to achieve a discharge burnup of about 32,000 MWD/T from enriched uranium as well as thorium. The design, however, requires a deliberate choice of a fairly high enrichment of about 5% in uranium rods to accommodate a large fraction of seedless thoria loading. At the above discharge burnup, the eUO_2 rods are naturally under-burnt and hence would contain significant residual ^{235}U. In a closed fuel cycle, the unburnt fissile fraction would, nonetheless, ease out the fuel requirement for subsequent fuel cycles. It must however be stated here that the higher enrichment is used in only half or less than half of the core loading with the rest being natural thorium. The equivalent mined uranium requirement, therefore, is either comparable or lower than that of any of the prevalent thermal power reactor designs. The neutron spectrum is a well-thermalized one especially in regions where fresh thoria clusters without any seed fuel rods are loaded. The thoria clusters serve as a kind of control absorbers for a duration of one fuel cycle. However at the end of one fuel cycle they contain adequate ^{233}U in them and hence would behave like regular fuel rods. Thereafter, they are juxtaposed with fresh seed fuel rods and irradiated for several fuel cycles, following a typical n-batch refueling scheme of a light water reactor (LWR). The spectrum in the mixed (U-Th) clusters is much softer than that of an LWR, but somewhat harder than that of a pressurized heavy water reactor (PHWR). There are two benefits of such a design. The softer spectrum helps to minimize the fuel enrichment needed for a given reactivity. The relatively harder spectrum helps to ensure a net zero or negative void reactivity coefficient, in the event of a loss of coolant accident (LOCA). Xenon override requirement is also substantially reduced.

The new reactor concept had been given the name ATBR (A Thorium Breeder Reactor). It must be stated that ATBR is not claimed to be a thermal breeder. Breeding of ^{233}U from natural thoria rods by merely placing them in the ambience of high thermal neutron flux is alone stressed and hence the name. When eUO_2 is considered as seed, ATBR would be an efficient ^{235}U to ^{233}U converter. Only when ^{233}U is used as seed, ATBR would tend to be close to a thermal breeder. The details of the reactor design are given in our earlier works[1-3]. The salient features are mentioned here. The reactor power is 600 MWe or 1875 MWt. It considers vertical pressure tubes arranged in a hexagonal lattice structure. D_2O moderator and boiling H_2O coolant are considered. Its engineering design is similar to that of a Steam Generating Heavy Water Reactor (SGHWR), which was designed and operated in the U.K.[5]. The geometry in a single fuel assembly is in the form of ring type fuel clusters as used in a PHWR. The cluster size is however very large. There are 84 fuel rods in a fuel assembly with a central moderator BeO block of 8.6 cm diameter. 54 thinner rods of enriched uranium oxide are placed in two rings, consisting of 24 and 30 fuel rods, which serve as seed zone, and 30 thicker rods of thorium oxide are placed in the outermost ring. The active fuel length is 360 cm. The thoria rods face directly the thermal flux incident from moderator. These thoria rods are assumed to be pre-irradiated in the same reactor for one fuel cycle duration. The core consists of 360 such (seed + irradiated thoria) fuel assemblies. In addition fresh thoria clusters of one batch size are uniformly spread in the core at twice the assembly lattice pitch. Some additional moveable thoria clusters are used to provide reactivity for xenon override. It may be mentioned here that moveable fuel control was used previously in the Light Water Breeder Reactor (LWBR), a thorium based thermal breeder which operated from 1977 to 1982 in the United States[6].

In the present study, other types of seed materials, viz., Pu or ^{233}U in thorium are investigated. The core characteristics are compared with the original design using enriched uranium as seed. For core analysis the fuel batch size is varied from 72 to 120 with 5, 4 or 3 batch refueling schemes. One batch size of fresh thoria clusters is also loaded in each of these cores. Additional 19 or 25 moveable thoria clusters are considered for xenon override. The lattice calculations are done by the code CLUB[7] with 69 group WIMS cross section library. The core calculations are done with the neutronics-cum-thermal hydraulics code TRISUL[8].

2. A COMPARATIVE STUDY OF THREE TYPES OF SEEDS

The geometrical description of the fuel cluster and core layout are given in the references 1 to 3. The feed enrichment for different seed types had to be iteratively determined after repeating the full set of lattice and core calculations a few times. The thoria rods are assumed to be pre-irradiated in the same core. The one group flux level in thoria rods was seen to vary from $(0.5 \text{ to } 2.5)\text{X}10^{14}$ n/cm^2/sec. In view of these variations, the two group homogenised cross sections of the ATBR fuel assemblies (seed + irradiated thoria) were parametrically generated by CLUB code for different starting fluence levels (different flux levels & cycle duration) in thoria rods. With a view to identify optimum fuel cycle length for each seed type, the fuel management strategy and the fuel cycle lengths were varied from 300 to 700 days. A core K_{eff} value which is reasonably close to and preferably higher than unity was aimed at. During the preparation of this paper, we noted an inadvertent error in the ATBR design evaluations, reported earlier with enriched uranium seed[1-3]. The cross section of free hydrogen instead of hydrogen bound in water was used. After this error was corrected, we found that the K_∞ decreased by nearly 2.5% at zero burnup and the difference gradually diminished to 0.2% at 50 GWD/T. The void reactivity effect also turned positive. We had to decrease the assembly lattice pitch to 30.5 cm from 32 cm to restore negative void coefficient and increase the enrichment to recover the core reactivity. The finalized pitch for Pu and ^{233}U seeds are respectively 30 cm and 29 cm. In case of Pu seed, the presence of a large fraction of ^{240}Pu of 24% at the beginning of life (BOL) posed additional problems. The K_∞ gets depressed significantly at zero burnup compared to K_∞ using other seeds. However, due to better fissile conversion, the slope of K_∞ with burnup is the least for Pu seeded fuel. In order to exploit this characteristic, we designed the Pu seeded core deliberately for much higher burnup than other types of seeds. Table-I gives a brief description of the finalized dimension and composition of the three seed materials. The middle ring consisting of Pu seeded fuel was made thinner so as to decrease the relative power peak in it. Fig.1 gives a typical comparison of the K_∞ curves of ATBR fuel with the three seeds. K_∞ for ^{233}U seeded fuel is the highest at zero burnup but falls more rapidly with burnup. At burnups above 15-20 GWD/T the K_∞ curve of Pu seeded fuel is much above the other two curves.

Equilibrium core studies were done for a large variety of reload batch sizes and n-batch loading schemes. We present here the results of batch sizes 72, 90 and 120 with 5, 4 and 3 batch fueling. In these cases, the total number of (seed + irradiated thoria) fuel assemblies is kept as 360. Additional fresh thoria clusters were 91, 109 and 145 respectively in these cores. The fuel cycle duration was varied from 300 effective full power days (efpd) to 660 efpd, depending on the seed and batch size.

Table-I Description of Seed Materials

Parameter	Seed Fuel Type					
	eUO_2		PuO_2 in ThO_2		$^{233}UO_2$ in ThO_2	
Seed	Enriched U		Reprocessed Pu		Reprocessed U	
	Inner	Outer	Inner	Outer	Inner	Outer
Fuel Clad ID/OD (mm)	10/11.4	10/11.4	10/11.4	9/10.4	10/11.4	10/11.4
No. of Fuel Rods	24	30	24	30	24	30
Seed Content (Wt. %)	6% ^{235}U	5% ^{235}U	20% PuO_2 in ThO_2	14% PuO_2 in ThO_2	6% UO_2 in ThO_2	5% UO_2 in ThO_2
Fissile fraction in Seed	1.0		0.745		0.941	
Composition of Seed	--		(^{239}Pu: ^{240}Pu: ^{241}Pu: ^{242}Pu) :: (69.3 : 24.1 : 5.2 : 1.4)		(^{233}U: ^{234}U: ^{235}U: ^{236}U) :: (93.73 : 5.84 : 0.416: 0.014)	

Note: 30 irradiated ThO_2 rods of ID/OD 12.6/14 mm is considered in the outermost ring surrounding the seed zone for all fuel types.

The loading schemes were individually optimized for each type of seed, batch size and cycle length. The optimized reloading patterns presented a variety of attractive floral designs in each core. A typical core loading pattern is schematically shown in Fig.2 for the 5-batch core with batch size of 72 and 300 efpd cycle length. It shows a curious star-like shape. Figs. 3a, 3b and 3c give the comparison of K_{eff} variation with cycle burnup for the three seeds and the three core loading. All thoria clusters remained fully inside throughout the fuel cycle and no fuel or control movements were considered. There was no soluble boron in the moderator. The reactivity and power distribution are intrinsically determined by the loading scheme and the burnup distribution thereof. The latter was determined by an iterative procedure. Typically four iterations were found to be adequate to get a converged burnup distribution and a stable core characteristics. The eUO_2 and $^{233}UO_2$ seeded cores behave alike. They are capable of operating for 330, 390 and 510 efpd for the three batch sizes 72, 90 and 120 respectively. Reactivity variation is just under ±4 mk for eUO_2 seed and is about ±11 mk for $^{233}UO_2$ seed. In view of the uncertainties in the cross section data and the calculation model, a K_{eff} value of 1.000 ± 0.005 is deemed to be a critical state. As mentioned earlier, the Pu seeded core was made sufficiently reactive. Though, the K_{eff} at the beginning of cycle (BOC) is closer to unity than for other types of seed, it rises significantly later with cycle burnup. The cycle length for Pu seeded cores are 390, 480 and 660 efpd for the three batch sizes. The cycle length could be much longer from reactivity considerations. However mechanical design considerations would restrict the achievable burnup in this case. Alternately if the Pu seed content is decreased to optimal value, the core reactivity at the BOC may become inadequate.

An interesting option for the closed fuel cycles seems to emerge from the above discussions. With ^{233}U seed, the core excess reactivity at BOC is fairly high (10-20 mk). With Pu seed the core excess reactivity at the end of cycle (EOC) is high (>10 mk). A judicious combination of these two types of seeded fuel can offer a core design with a bare minimum core excess reactivity of <5mk for very long cycle duration. Cycle lengths extending to 2 years or more is particularly attractive for closed fuel cycles since it would allow more time for out of pile fuel handling, i.e., for reprocessing and the prior cooling period and re-fabrication. Such small reactivity fluctuations can be met mostly by varying the coolant inlet subcooling.

Figs. 4a, 4b and 4c compare the gross power peaking factors (3-D) for the above cores. Radial and axial peaking factors are compared in Figs. 5a, 5b and 5c and Figs. 6a, 6b and 6c. It is seen that the gross peaking factor decreases with cycle burnup. It is as low as 1.3 at EOC for longer cycle lengths. The radial peak is lower and axial peak is higher for Pu seed. This is due to the lower K_∞ value of Pu seeded fuel at zero burnup and flatter trend with burnup. It may be stated that if the core reload pattern is well designed, the core characteristics remain stable and improve intrinsically with cycle burnup for all types of seeds.

Figs. 7a, 7b and 7c give the discharge burnup, seed input and output per fuel cycle in kg for the three seed types. The discharge burnup for Pu seed is much higher since the seed inventory was deliberately chosen high to allow for the high ^{240}Pu content. Though seed input is too large for Pu seed, the seed output is also proportionately large. The output to input ratios are also indicated in Figs. 7a, 7b and 7c. This ratio is obviously the highest for $^{233}UO_2$ seed. For a batch size of 120 FAs, the ratio is 91.5%. If the fissile content of the additional ThO_2 clusters is added, this ratio increases to 94.7%. To enhance the fissile material output, one can consider at least one layer of thoria blanket surrounding the present core. A separate fuel management scheme for these clusters can be devised. Half of such clusters can be fresh and the others irradiated for one fuel cycle. If the cycle length of about 600 days or more is considered, it is expected that the ^{233}U produced in about 48 to 60 clusters in two fuel cycles can make up for the shortfall in output to input ratio of about 5%. In this case, the $^{233}UO_2$ seed type can become a thermal breeder. However, since the fissile content decreases with every recycling, we can expect this option to be just nearly self-sustaining.

CONCLUSIONS

The thorium breeder reactor concept which was studied earlier with eUO_2 seed, has now been analyzed with Pu and ^{233}U seeds as well. All the three seed types exhibit similar core characteristics. Absence of external reactivity control mechanism and the near zero void coefficient of the fuel design, make the ATBR concept inherently safe. The Pu seeded core accommodates nearly 58% as fresh thoria rods with no feed enrichment. The β_{eff} (delayed neutron fraction) is about 3.5 mk. This would improve the dynamic behavior of this core in comparison to an all-Pu core. Further work is underway to increase the conversion ratio in all the three seed types by incorporating a separate fuel management scheme for some additional ThO_2 clusters in and around the core.

The studies point to two phases of fuel cycle options. In phase-I, enriched uranium is used and there will be production of large amounts of ^{233}U and smaller quantity of Pu. No reprocessing is needed in this phase. In phase-II, the reactor considers the use of Pu or better, ^{233}U as seed material in thorium. Of these, the fuel cycle option with ^{233}U as seed can be nearly self-sustaining. Pu seeded clusters can be used in a limited way along with ^{233}U seed. The presence of ^{240}Pu can be used vantageously to suppress the high excess reactivity at BOC and provide reactivity later at EOC. This can lead to a core design with small excess reactivity for very long cycle duration. Smooth transition from phase-I to phase-II is feasible with no significant modification in the core design.

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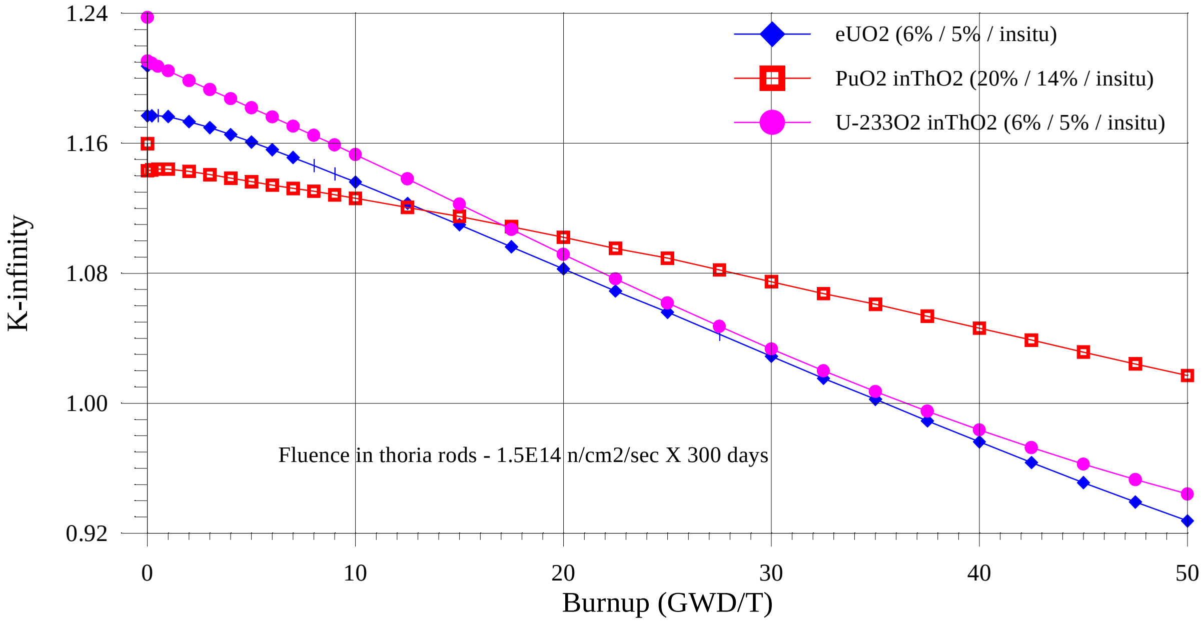


Fig.1 Comparison of K-inf vs Burnup for Different Seeds

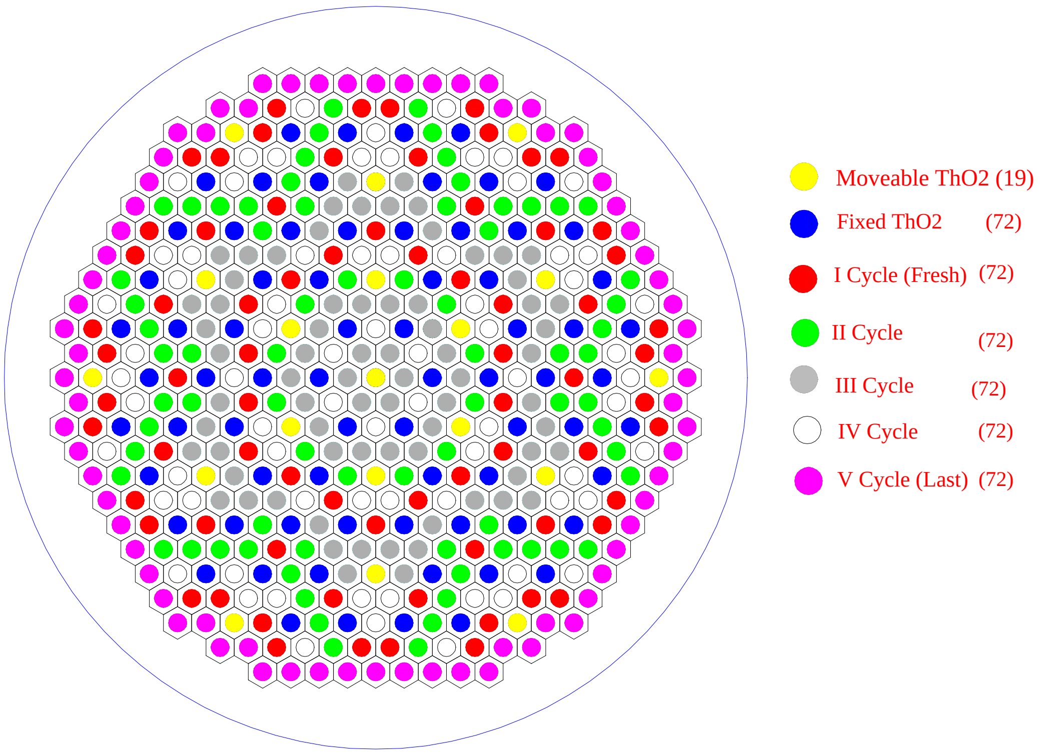


Fig.2 ATBR Core - 360 (eUO2+ThO2) + 91 ThO2 Fuel Clusters
72 Assemblies/Batch - 5 Batches - Optimized Loading Pattern

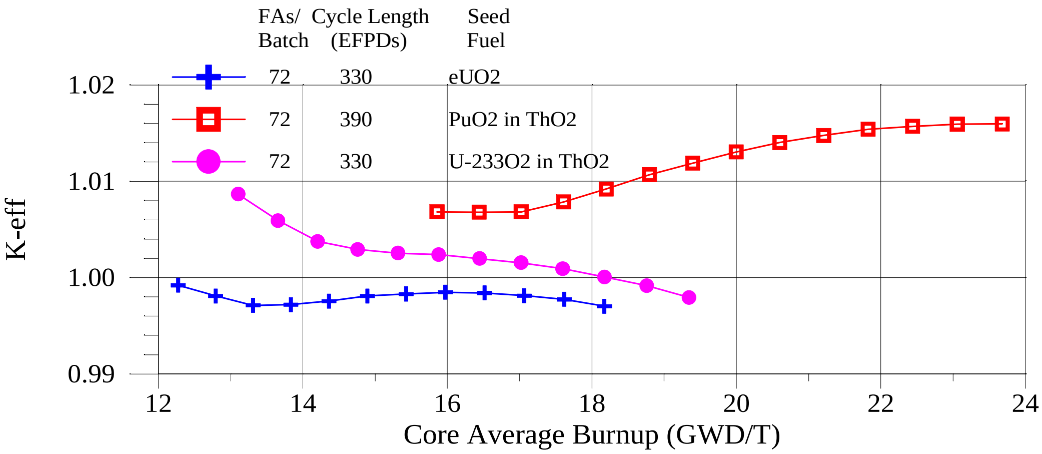


Fig.3a Comparison of K-eff vs Cycle Burnup for 5 Batch Fueling

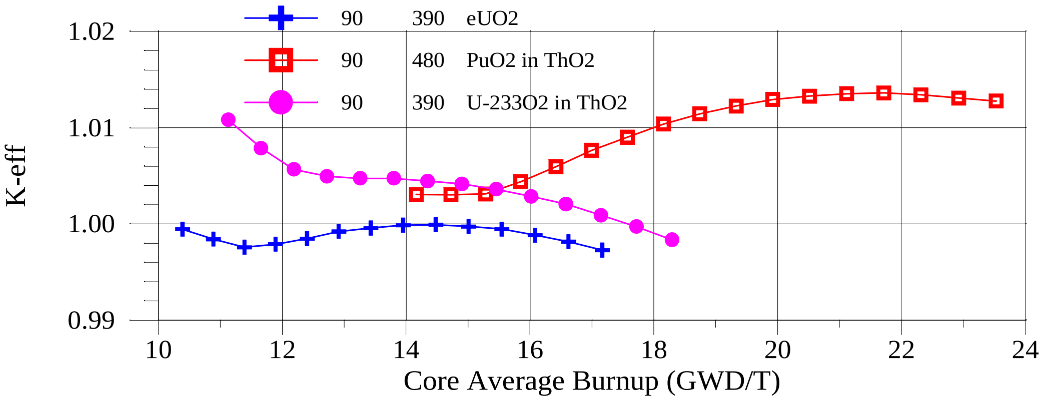


Fig.3b Comparison of K-eff vs Cycle Burnup for 4 Batch Fueling

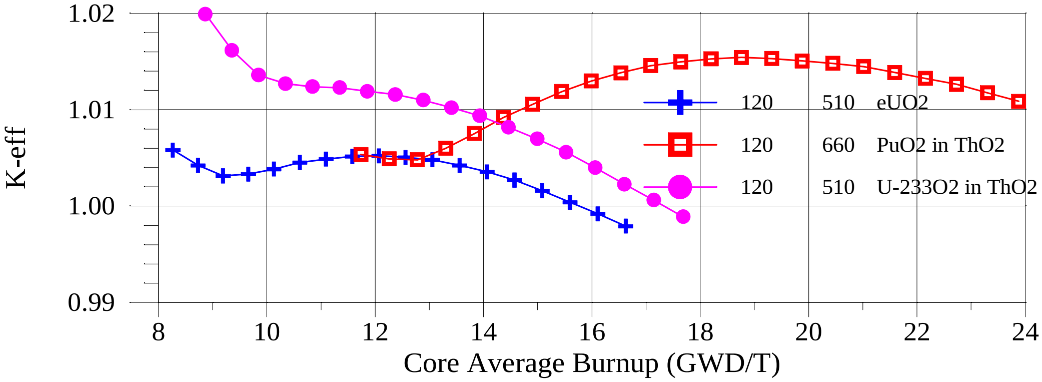


Fig.3c Comparison of K-eff vs Cycle Burnup for 3 Batch Fueling

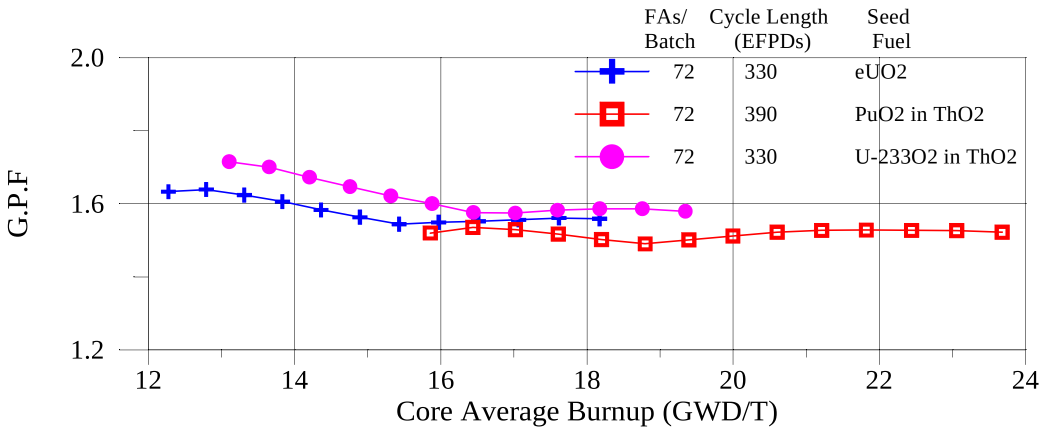


Fig.4a Comparison of Gross Peaking Factor vs Cycle Burnup for 5 Batch Fueling

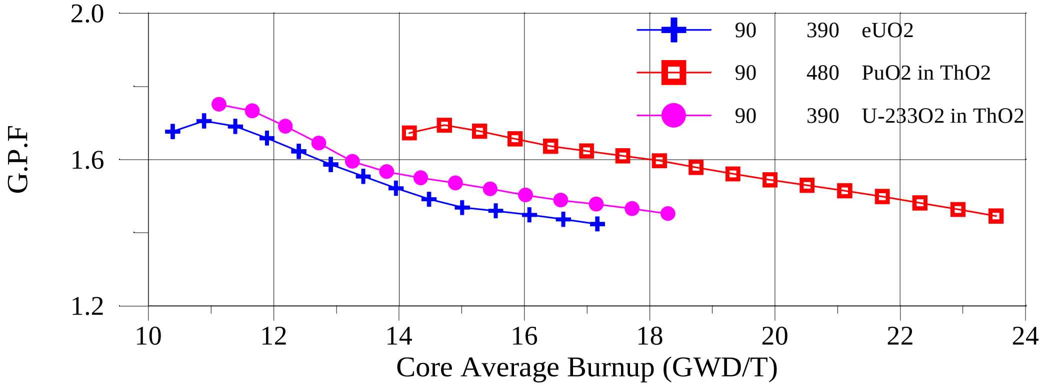


Fig.4b Comparison of Gross Peaking factor vs Cycle Burnup for 4 Batch Fueling

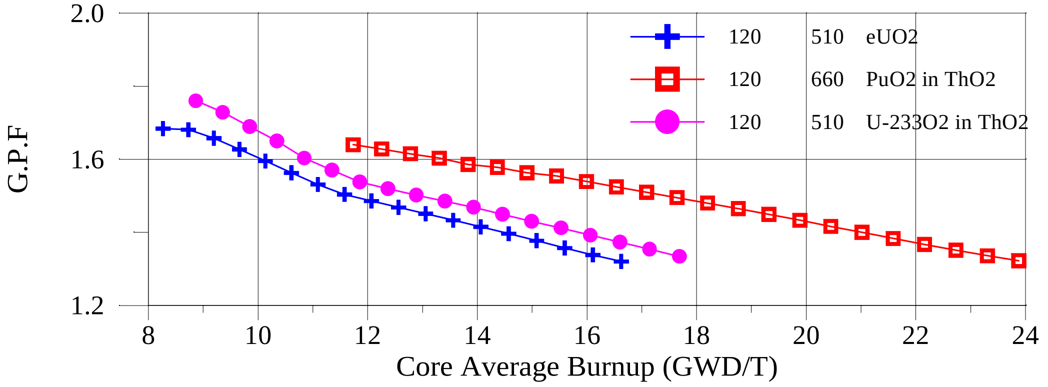


Fig.4c Comparison of Gross Peaking Factor vs Cycle Burnup for 3 Batch Fueling

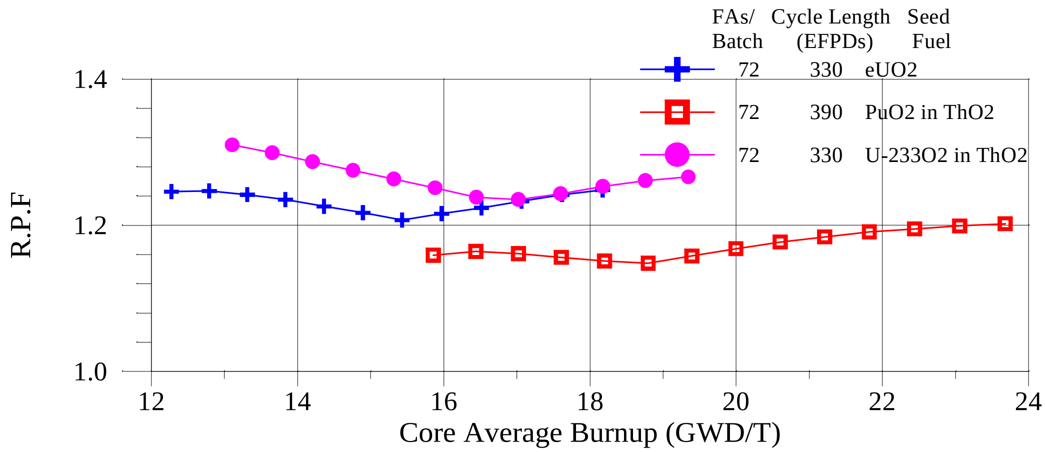


Fig.5a Comparison of Radial Peaking Factor vs Cycle Burnup for 5 Batch Fueling

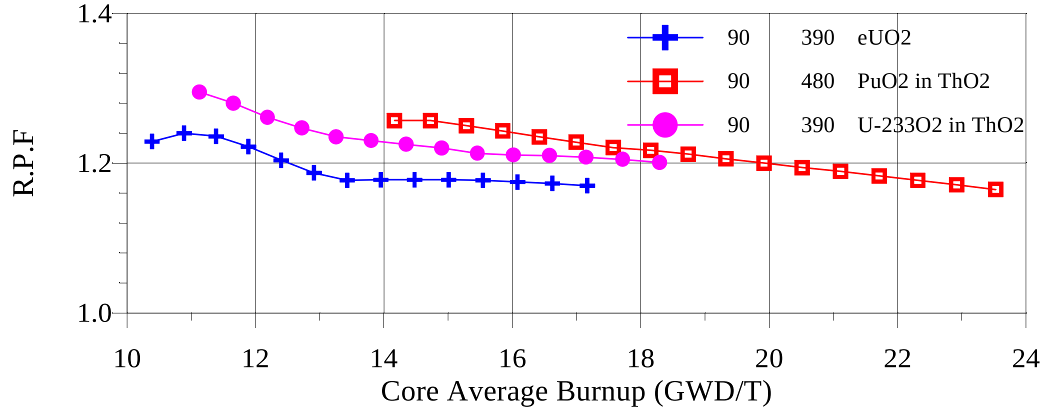


Fig.5b Comparison of Radial Peaking factor vs Cycle Burnup for 4 Batch Fueling

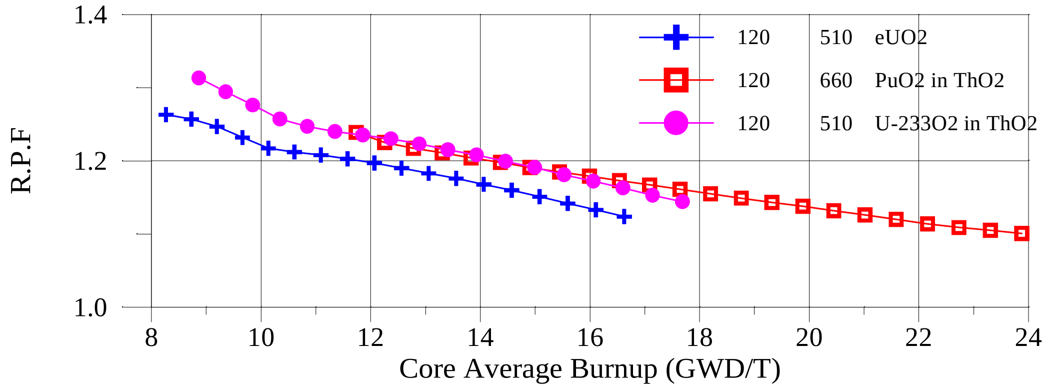


Fig.5c Comparison of Radial Peaking Factor vs Cycle Burnup for 3 Batch Fueling

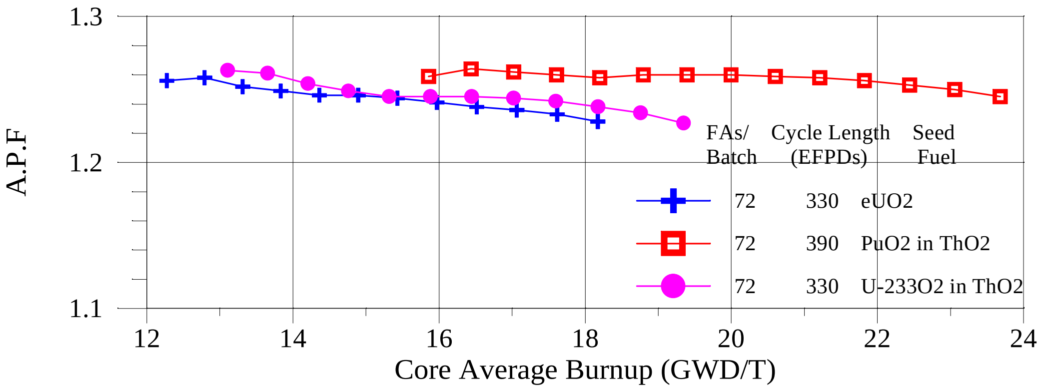


Fig.6a Comparison of Axial Peaking Factor vs Cycle Burnup for 5 Batch Fueling

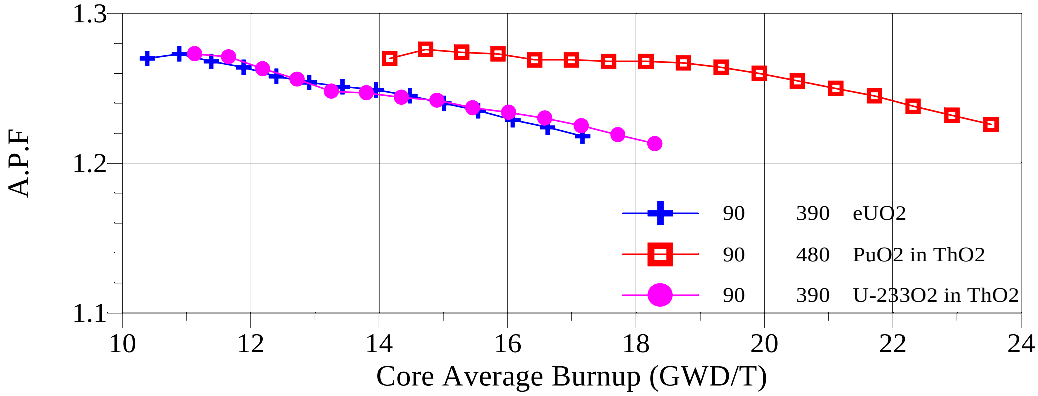


Fig.6b Comparison of Axial Peaking factor vs Cycle Burnup for 4 Batch Fueling

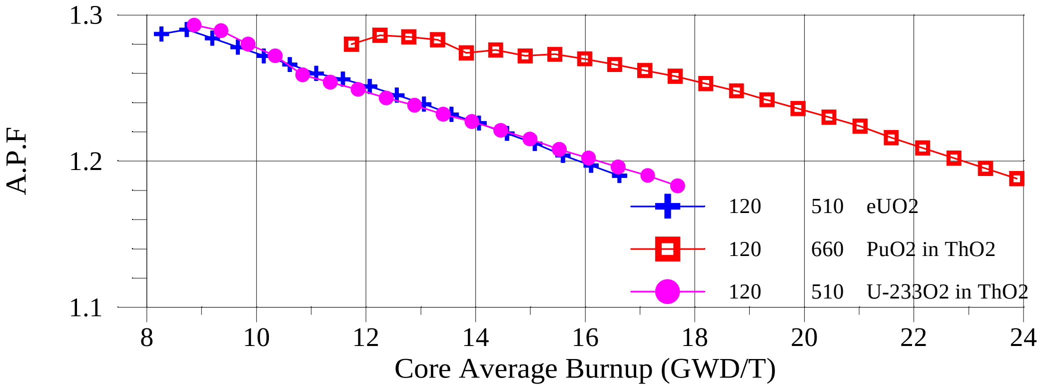
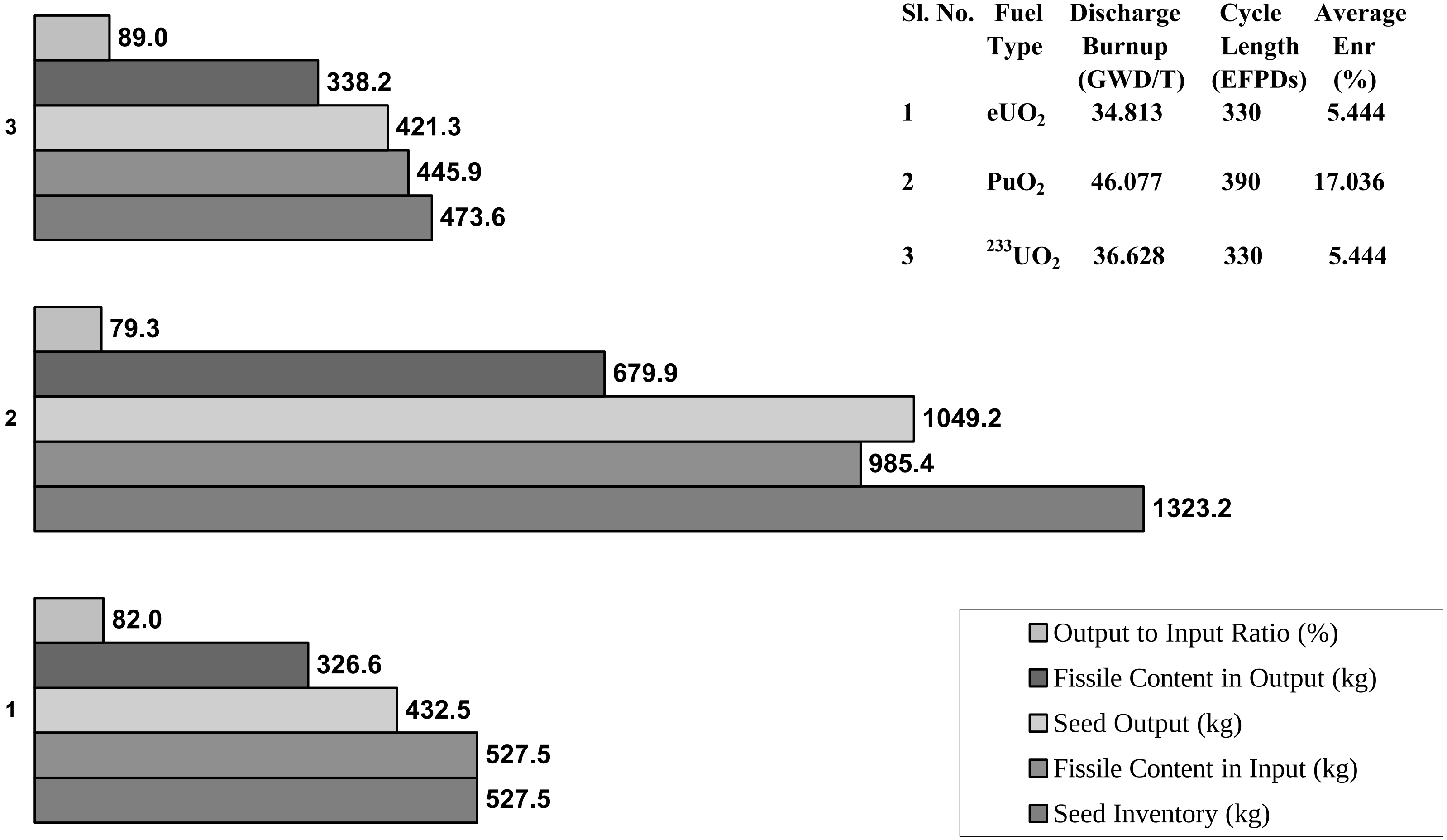


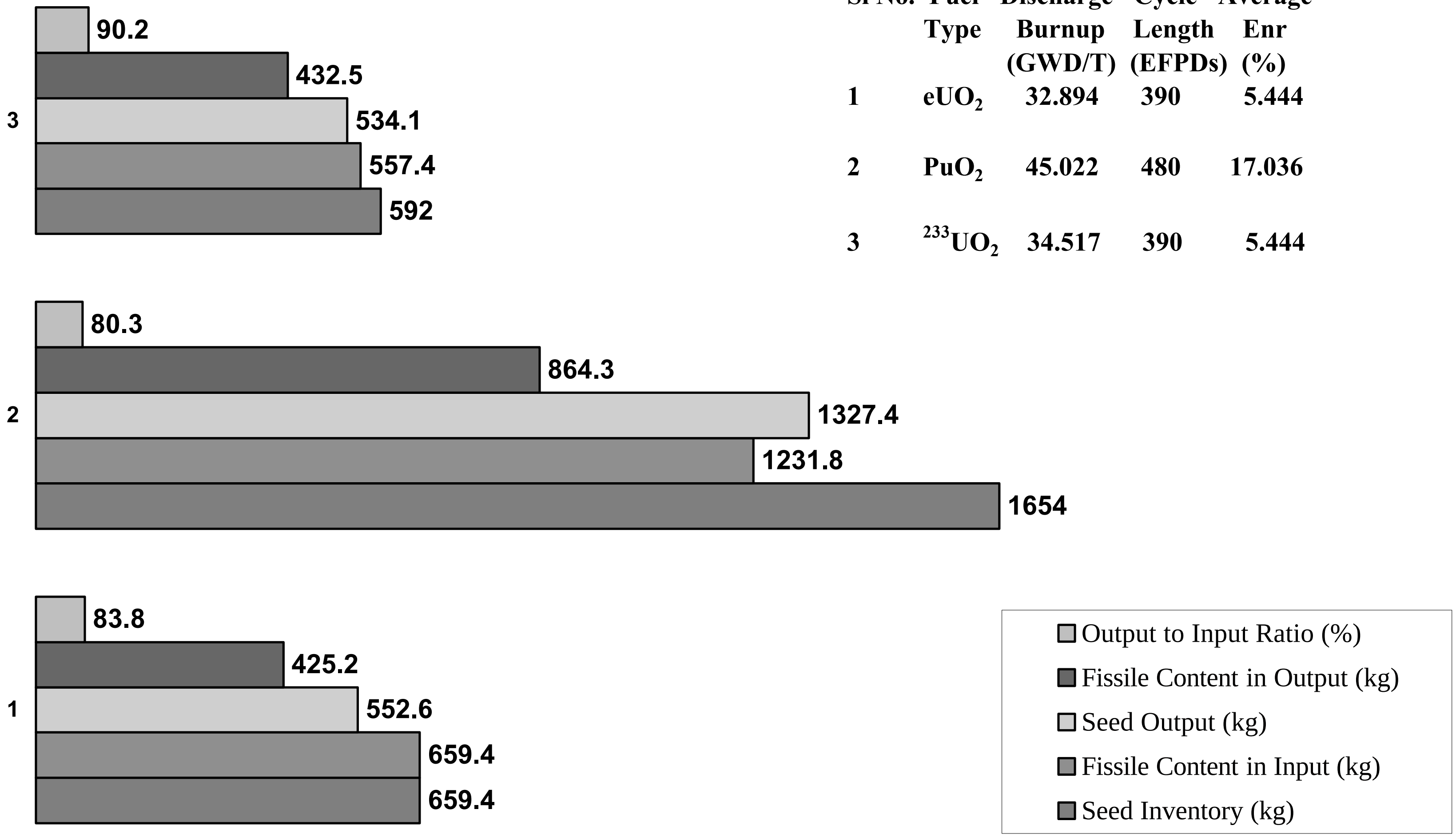
Fig.6c Comparison of Axial Peaking Factor vs Cycle Burnup for 3 Batch Fueling

Fig.7a ATBR - COMPARISON OF SEED INPUT/OUTPUT FOR VARIOUS TYPES OF FUEL
(72 FAs/BATCH)



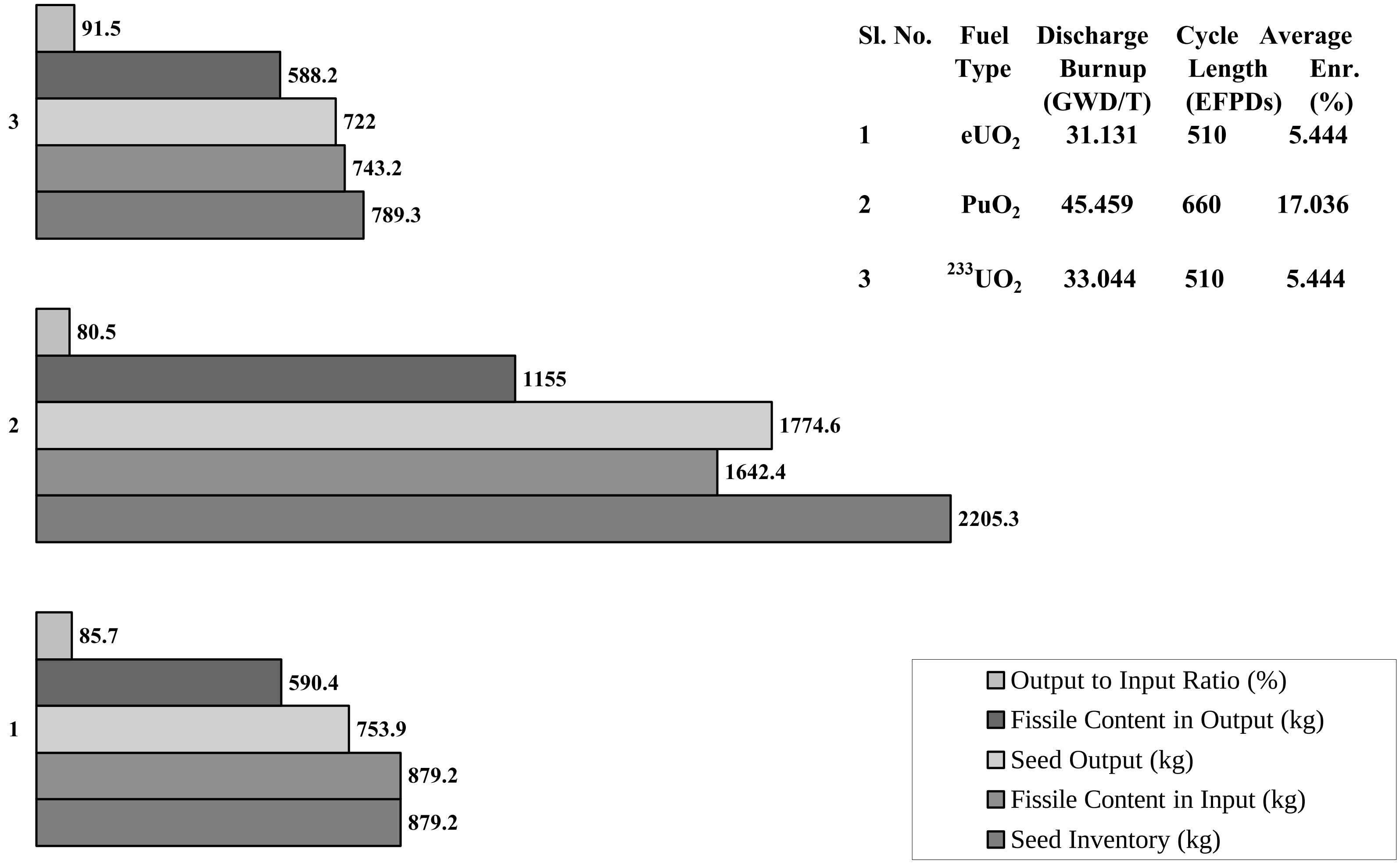
Sl. No.	**Fuel Type**	**Discharge Burnup (GWD/T)**	**Cycle Length (EFPDs)**	**Average Enr (%)**
1	**eUO_2**	**34.813**	**330**	**5.444**
2	**PuO_2**	**46.077**	**390**	**17.036**
3	**$^{233}UO_2$**	**36.628**	**330**	**5.444**

Fig.7b ATBR - COMPARISON OF SEED INPUT/OUTPUT FOR VARIOUS TYPES OF FUEL (90 FAs / BATCH)



Sl No.	Fuel Type	Discharge Burnup (GWD/T)	Cycle Length (EFPDs)	Average Enr (%)
1	eUO_2	32.894	390	5.444
2	PuO_2	45.022	480	17.036
3	$^{233}UO_2$	34.517	390	5.444

Fig.7c ATBR - COMPARISON OF SEED INPUT / OUTPUT FOR VARIOUS TYPES OF FUEL
(120 FAs / BATCH)



Sl. No.	Fuel Type	Discharge Burnup (GWD/T)	Cycle Length (EFPDs)	Average Enr. (%)
1	eUO_2	31.131	510	5.444
2	PuO_2	45.459	660	17.036
3	$^{233}UO_2$	33.044	510	5.444