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A conceptual high flux reactor design with scope for use in ADS applications

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Abstract. A 100 MWt reactor design has been conceived to support flux level of the order of 10^{15} n/cm^2/s in selected flux trap zones. The physics design considers high enriched metallic alloy fuel in the form of annular plates placed in a D_2O moderator tank in a hexagonal lattice arrangement. By choosing a tight lattice pitch in the central region and double the lattice pitch in the outer region, it is possible to have both high fast flux and thermal flux trap zones. By design the flux level in the seed fuel has been kept lower than in the high flux trap zones so that the burning rate of the seed is reduced. Another important objective of the design is to maximize the time interval of refueling. As against a typical refueling interval of a few weeks in such high flux reactor cores, it is desired to maximize this period to as much as six months or even one year. This is possible to achieve by eliminating the conventional control absorbers and replacing them with a suitable amount of fertile material loading in the reactor. Requisite number of seedless thorium–aluminum alloy plates are placed at regular lattice locations vacated by seed fuel in alternate fuel layers. It is seen that these thorium plates are capable of acquiring asymptotic fissile content of 14 g/kg in about 100 days of irradiation at a flux level of 8×10^{14} n/cm^2/s. In summary, the core has a relatively higher fast flux in the central region and high thermal flux in the outer region. The present physics design envisages a flat core excess reactivity for the longest possible cycle length of 6 months to one year. It is also possible to modify the design for constant subcriticality for about the same period or longer duration by considering neutron spallation source at the centre and curtailing the power density in the inner core region by shielding it with a layer of thoria fuel loading.

Keywords. High flux reactor; thermal neutron flux traps; fast neutron flux traps; long fuel cycle duration.

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1. Introduction

High flux reactors in the world follow various designs, but have broad similarities as well. The objective is to achieve either high level of thermal neutron flux or high fast neutron flux. High thermal flux of the order of 2×10^{15} n/cm^2/s is required for the production of ^{252}Cf in sizable quantities in a reasonable period of few months. Production of other important isotopes used in medical industry is also achieved. High fast neutron flux with energy >1 MeV is useful for the study

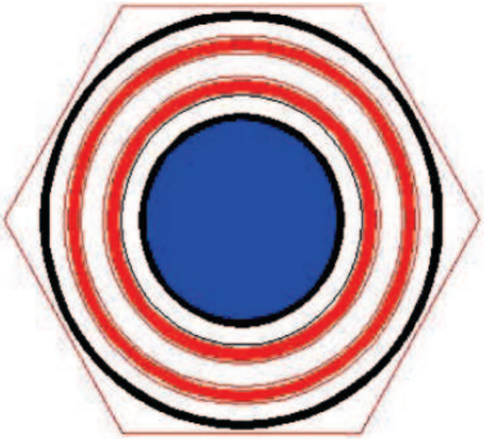

Figure 1. Annular plate-type fuel design for HFTR core.

of irradiation behaviour of reactor materials. In a simple design, highly enriched uranium metallic alloy in annular cylindrical shape is placed in D_2O tank with D_2O coolant as in the case of Savannah River Laboratories (SRL) [1]. In this reactor, uniform high thermal flux is achieved in the entire reactor. The core consists of 107 assemblies with $\sim$150 g ^{235}U/FA. The ^{235}U inventory is $\sim$16 kg. The reactor power is 735 MWt resulting in an average heat flux value as high as 733 W/cm^2. The heat removal is achieved by using thin plate-type fuel with large heat transfer area, metallic alloy with high thermal conductivity. The coolant velocity is 70 ft/s or 21.3 m/s. With the inlet temperature kept at 20°C and a core ΔT of <50°C, it is possible to consider low pressure of the order of 6 kg/cm^2 for this high flux reactor core. The core excess reactivity has to be controlled by heavy density of strong absorber control which partly off-sets the availability of high neutron flux. The control also results in flux distortion and high peaking factors. The rapid change in reactivity with burnup calls for refueling interval of the order of 2–3 weeks. High neutron flux also results in excessive override reactivity for xenon (620 mk) and samarium (100 mk).

The design philosophy of the proposed High Flux Test Reactor (HFTR) is to achieve the two objectives of high thermal and high fast neutron flux in the same core. D_2O is considered as moderator and coolant. Instead of having uniform high flux in the core, it is planned to keep the flux in ambience to be reasonably low ($\sim 2 \times 10^{14}$ n/cm^2/s) and achieve high thermal and fast flux of the order of 10^{15} n/cm^2/s in selected irradiation locations only. In view of the relatively low flux prevalent in the entire core, it is planned to achieve longest possible fuel cycle life of six months to one year.

The principles to achieve this objective may be stated as follows. Use of high enriched uranium with minimum fertile content does not have a possibility to replenish itself. It is proposed to consider Th–Pu mixed fuel in either oxide form or in alloy form. It has been demonstrated that this fuel can be exploited for achieving two year cycle length with no refueling and also with no significant control maneuvers for power operation of a conceptual reactor ATBR at 600 MWe [2]. Hence it

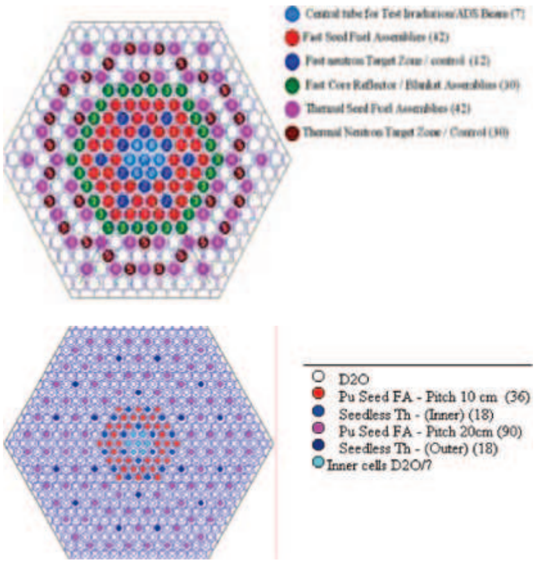

Figure 2. (**a**) Tentative HFTR 100 MWt core layout-1. (**b**) Tentative HFTR 100 MWt core layout-2.

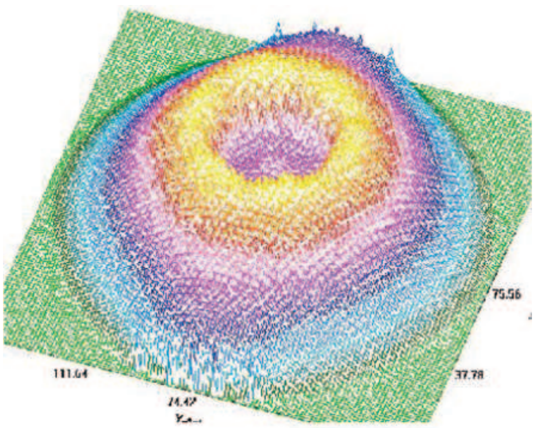

Figure 3. Thermal flux distribution at the core mid-plane.

is suggested to adopt the design features such as (i) high fissile loading in small volume, (ii) fissile feed in one third fraction of the fuel rods, (iii) minimization of external control inventory during power operation. The control requirement is minimized by loading equivalent amounts of thorium and configuring them suitably. *In situ* breeding of ^{233}U helps in achieving flatter reactivity variation with burnup thereby extending the core life as much as possible.

The principle for achieving relatively high epithermal flux is to consider a tight lattice pitch in the central region of the core. High thermal flux is achieved in the

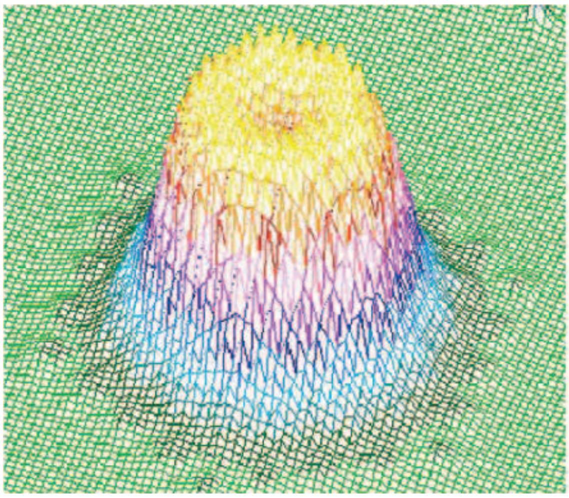

Figure 4. Fast flux distribution at the core mid-plane.

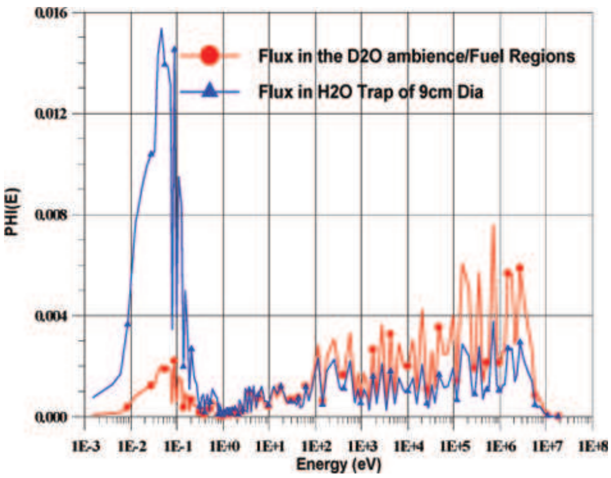

Figure 5. Enhancement of thermal flux by annular H_2O in D_2O.

outer region by adopting the double lattice pitch size. Annular light water trap zones are proposed where local enhancement of thermal flux is needed.

The control design philosophy is as follows. The fast shutdown system shall have minimum worth of the order of 2 to 3β just adequate to shutdown from any reactor state. Shutdown hold is achieved by slow moving devices with fairly high worth to provide adequate shutdown margin under the most reactive state of the core. The regulating control devices would cater to temperature loads of fuel and coolant, saturated xenon and samarium loads, transient ^{233}U loads following any shutdown. The burnup reactive load is minimized. It is expected to be controlled by reactivity gain in thorium fuel zones. One cycle of (duration of 300 days) irradiated thorium

Table 1. Design parameters of high flux test reactor.

Parameter	Units	Value
Power	MWt	100
Cycle length	Days	300
Active core height	cm	100
Description of seed fuel rods		
No. of seed fuel rods/FA		24
Pin ID/OD	mm	4/5
Pitch circle diameter	mm	53.48
PuO_2 in ThO_2	%	30
Pu mass per pin	g	99.4
No. of seeded FAs		108
No. of seeded FAs/batch		36
Description of seedless fuel rods		
No. of seedless ThO_2 rods/FA		30
Pin ID/OD	mm	5.44/6.44
Pitch circle diameter	mm	80.6
PuO_2 in ThO_2	%	0
Seedless thoria		36+18
No. of seedless FA/batch		36+18
Total heavy metal in core	kg	1194
Total Pu inventory in core	kg	90
Hexagonal lattice pitch (Inner)	cm	10
(Outer)	cm	20
Average linear heat rating	w/cm	248
Discharge burnup of seed fuel rods	GWD/T	60–80
Discharge burnup of seedless fuel rods	GWD/T	50–70

forms the outer shell in each seed fuel assembly in equilibrium core. The process of breeding ^{233}U continues for three more fuel cycles and it is expected to achieve nearly similar high discharge burnup from both Pu seeded fuel and the initially seedless thorium fuel.

2. Present status of work

The geometry of annular plate fuel is shown in figure 1. Table 1 gives the general description of core design parameters. The schematic core lay-out of the tentative high flux test reactor core are shown in figures 2a and 2b. In figure 2a a ring layer of fertile thoria fuel zone separates the inner and outer zones.

In figure 2b, this region has been eliminated. Typical co-existence of high epithermal and thermal flux in the inner and outer regions is illustrated in figures 3 and 4. Figure 5 illustrates the enhancement of local thermal flux by using a light water trap in the D_2O moderator ambience. Figure 6 shows the k_∞ variation for seedless thoria fuel. It is seen that the rise is steeper at higher flux, but falls to

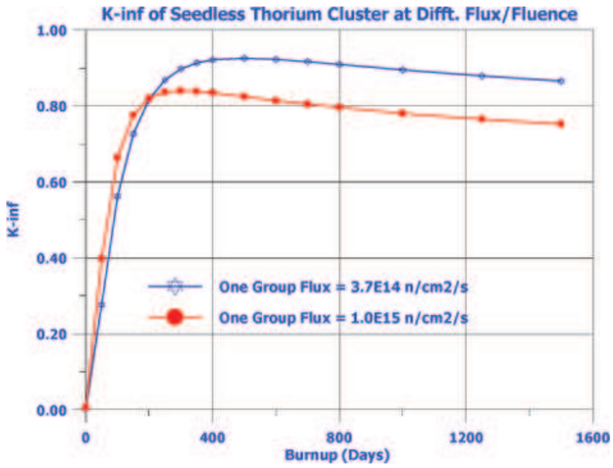

Figure 6. Variation of K_∞ with burnup in Th cluster at different flux/fluence.

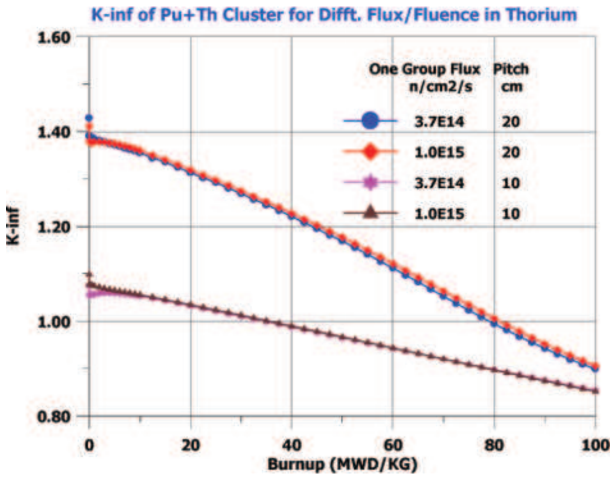

Figure 7. Variation of K_∞ with burnup in Pu+Th cluster for different flux/fluence in thorium.

lower value asymptotically. At tight lattice pitch of 10 cm, it was seen that one group flux level of 10^{15} n/cm^2/s is achieved. However, due to the high epithermal resonance capture cross-section of ^{233}Pa, the decay route to ^{233}U is bypassed and ^{234}U is directly formed, resulting in lower reactivity asymptotically. Figure 7 shows the k_∞ variation of combined fuel cluster-inner layer with Pu seed and outer layer with *in situ* bred ^{233}U in thorium. For tight lattice pitch of 10 cm, the k_∞ value is much lower than that for the 20 cm pitch. The burnup reactivity swing is lower for the tight lattice pitch. These variations are smaller than the values one would get if one considers uniformly distributed fissile seed in the inner and outer fuel layers.

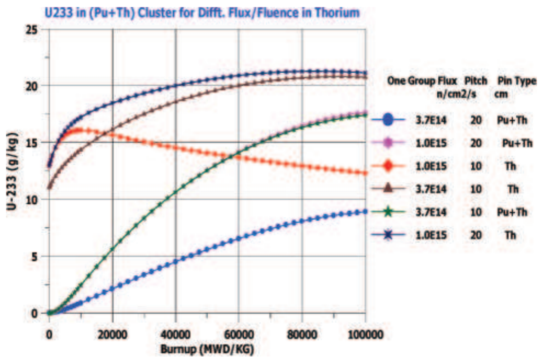

Figure 8. Variation of ^{233}U with burnup in Pu+Th cluster for different flux/fluence in thorium.

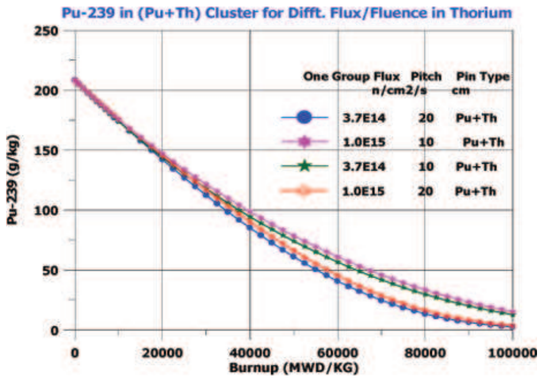

Figure 9. Variation of ^{239}Pu with burnup in Pu+Th cluster for different flux/fluence in thorium.

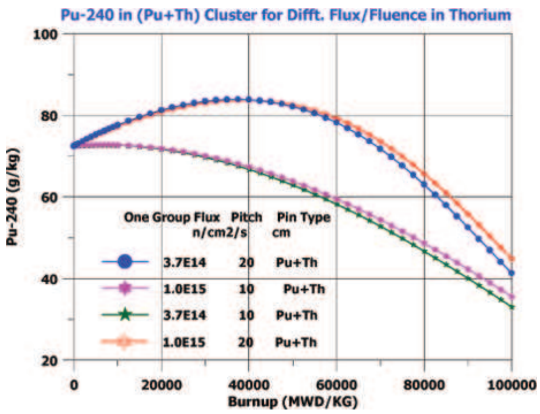

Figure 10. Variation of ^{240}Pu with burnup in Pu+Th cluster for different flux/fluence in thorium.

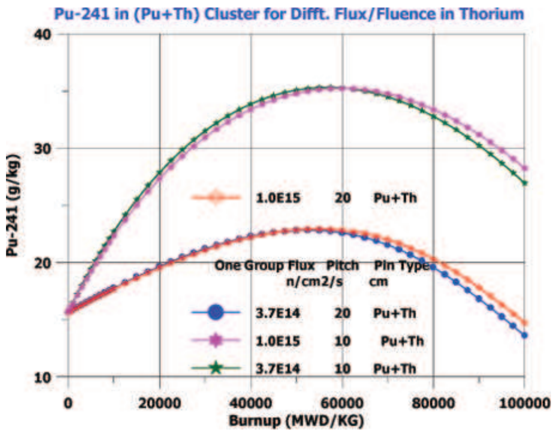

Figure 11. Variation of ^{241}Pu with burnup in Pu+Th cluster for different flux/fluence in thorium.

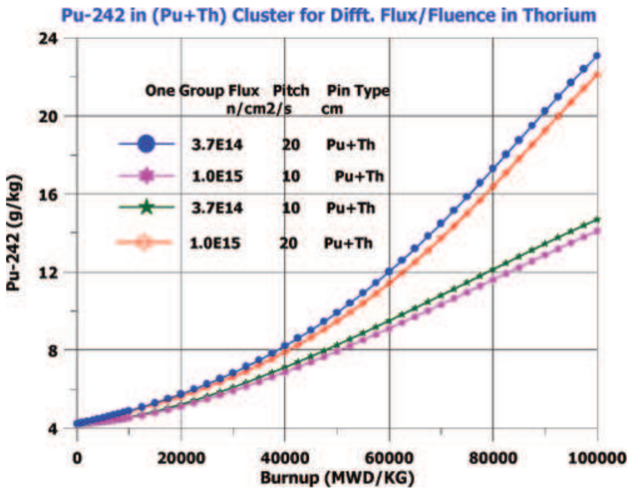

Figure 12. Variation of ^{242}Pu with burnup in Pu+Th cluster for different flux/fluence in thorium.

Figure 8 shows the ^{233}U variation in the inner and outer fuel layers up to burnup of 100 GWD/T. It is seen that ^{233}U accumulates up to 12 g/kg in the inner seed with initial Pu content of 30%. In the outer layer, the initial ^{233}U content at zero burnup is the *in situ* bred value in the previous fuel cycle. It is seen to be more than the asymptotic value indicated above. The relative power share of seedless thoria rods is initially 0.4 and increases to 0.8 near discharge burnup. The variations of Pu isotopes in the seed fuel layer are shown in figures 9–12.

The physics design is being further optimized for minimization of burnup reactivity swing. Since the core is small, the task is rendered more difficult. Tuning of the relative mass fraction of Pu-seeded fuel and seedless thoria to get core $k_{\rm eff}$ variation over 300 days to be within ±0.5% is still in progress.

The thermal hydraulic design, control design will be taken up after the physics design is nearly satisfactory. Redesigning the core central region to accommodate ADS beam would be considered at later stages. It is more appropriate to design a subcritical core in a power reactor version of this concept.

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