Physics design of a safe and economic thorium reactor

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Thorium does not have intrinsic fissile content unlike uranium. ^{232}Th has nearly three times thermal absorption cross-section compared to ^{238}U and hence requires much larger externally fed fissile content compared to uranium-based fuel. These factors give a permanent economic competitive edge to uranium. Introduction of thorium acts as additional reactivity load and also distorts the power distribution. We had evolved a new reactor concept called 'A Thorium Breeder Reactor' (ATBR), where the above disadvantages are turned into advantages. Seedless thorium is introduced in separate clusters as pure absorber rods to suppress the initial excess reactivity and after one fuel cycle, irradiated thoria rods are integrated with fresh seed fuel rods to form the regular fresh charge for each fuel cycle. The high fissile conversion rate in thoria rods enables extension of the life of the fuel cycle. It is possible to achieve a high discharge burn-up of ~50,000 MWD/T from both seed fuel rods and seedless thoria rods. Here we elucidate the physics design principles of ATBR. Use of PuO_2 seeded thoria fuel is found to give excellent core characteristics like two-year cycle length with nearly zero control manoeuvres, fairly high seed output to input ratio and intrinsically safe reactivity coefficients.

Keywords: ATBR, physics design, thorium, uranium.

THOUGH the mechanical and thermal properties and irradiation behaviour of thorium are better than that of uranium and the physical characteristics like η of the man-made fissile isotope ^{233}U are the best in thermal reactors, the overall economic considerations and the problem of handling high gamma activity of the short half-life isotope ^{232}U (72 years) and its decay products have been hindering the use of thorium in a major way. Tangible solution to these problems may be found in the course of time. Notwithstanding the above, we have evolved a reactor concept in which the reprocessed fuel component is reduced to just 50% by weight and the other 50% is thorium in its natural form. This reactor concept is called 'A Thorium Breeder Reactor' (ATBR). The phrase 'Thorium Breeder' is deliberately coined to suggest a concept that promotes large-scale use of thorium in the reactor with high excess reactivity and high neutron flux ambience. The reactor is not claimed to be a 'breeder' in the conventional sense.

ATBR can consider the seed material as eUO_2, PuO_2 in ThO_2, or $^{233}UO_2$ in ThO_2 at later stages. Large-scale induction of seedless thoria rods is a unique feature of the ATBR concept[1–6]. Among the above types of seeds, ATBR with PuO_2-seeded thoria fuel is found to give excellent core physics characteristics like longest possible cycle length of about two years with nearly zero control manoeuvres, fairly high seed output-to-input ratio and intrinsically safe reactivity coefficients. We would elucidate here the design principles which were used to achieve these characteristics. Results of the analysis with the latest 172 group library in WIMS/D format obtained from IAEA as part of the IAEA Co-Ordinated Research Programme on WIMS library update project will be presented[7,8].

This article delineates mainly the physics ideas used to evolve the reactor concept. The engineering design of ATBR is similar to the Advanced Heavy Water Reactor (AHWR) being actively pursued in DAE, and is based on the Steam Generating Heavy Water Reactor design, developed originally in UK[9]. The Fugen reactor which operated in Japan for more than two decades adopted this reactor engineering design successfully[10]. ATBR considers hexagonal lattice arrangement, while the other reactors mentioned here consider square lattice arrangement.

Physics design considerations

A fuel cycle length of two-year operation with no on-power fuelling would help in easing out the problems of refuelling and also provide the much needed lead time for reprocessing, prior cooling and refabrication of fuel assemblies. In this context, we know that long fuel cycle duration would necessarily mean a large excess reactivity inventory and control thereof. This is normally achieved by increasing the feed enrichment and correspondingly large control inventory. A variety of reactivity control means like soluble boron, control rods and burnable poison rods of Gd or boron type are normally employed. In such a situation, any removal of absorption such as inadvertent withdrawal of control rod or boron dilution would have the potential to cause some reactivity-initiated transient. Further, neutron absorption in these absorbers results in loss of neutrons and is not gainfully utilized.

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One unique feature of nuclear energy, unlike energy from fossil fuels, is the possibility to produce new fissile atoms through neutron capture in fertile atoms when some fissile atoms are being consumed, i.e. nuclear fuel has a means of rejuvenating itself while being spent. We would be able to prolong the nuclear energy extraction process if a large fraction of the fissile atoms that are consumed can be replenished with new fissile atoms in the same reactor and within the same fuel cycle duration. This would require a delicate balance of the fissile depletion and production rates. For this exercise to be meaningful, the process should last for as long a time as possible. If we can eliminate nearly all external absorbers like control, boron and Gd and load equivalently large mass of fertile material like thorium in the core, it would initially act like a pure neutron absorber, but eventually turn into fuel after acquiring sufficient amounts of the *in situ*-bred new fissile atoms. Elimination of external absorbers for reactivity control would mean that the core excess reactivity should be zero or small all the time and for as long a duration as possible. In other words, the core composition of fissile and fertile materials should be designed in such a way that the reactivity loss by fissile depletion is nearly balanced by the reactivity gain of new fissile formation at all times. This does not happen in the present-day power reactors because fissile depletion is normally at a much higher rate than the rate of production of new ones. This is because the absorption reaction rate in the fissile atoms invariably dominates over the fertile capture reaction rate. The imbalance is much more for higher feed enrichments. The rates may become comparable only after considerable depletion of the initial fissile feed, but the fuel may have to be discharged much sooner from reactivity considerations. Natural uranium reactors have the best conversion ratio. But the fuel residence time is as low as six months to one year and one requires continuous refuelling for the equilibrium core. Since the core excess reactivity is low, one cannot load any significant amount of other fertile material like thorium in the equilibrium core using natural uranium feed. In enriched reactor systems, the reactivity fall due to fuel depletion cannot be matched by intrinsic fissile formation within the same fuel rods. Even in fast reactor systems where the η value of Pu is close to three, the fertile to fissile conversion happens at a lower rate than fissile depletion in the main core. Fast reactors become breeder mainly through cumulative capture reactions in external blanket regions. It may be noted that the flux level in blanket regions is 3–6 times lower than the central core regions. This means the fissile formation reaction rate in the blanket region is much lower. In the core region, fissile depletion reaction rates invariably dominate over the fissile production rate within the same fuel rod and then become comparable only near the discharge burnup. The internal and total breeding ratio of typical fast reactors is reported as 0.71 and 1.27 for PuO_2-seeded ThO_2[11]. In our view, there is no reactor design, fast or thermal, which gives a continuous fissile growth within a span of single fuel cycle. In the ATBR core design, we attempt to maximize the seed output-to-input ratio in a fuel cycle. Later, we would present a comparison of this ratio with typical values of other thermal power reactors.

In short, it is recognized that there is need for a paradigm shift in the type of reactor design, where reactivity loss due to fissile depletion can be intrinsically compensated by fissile formation in the same reactor.

As seen above, there are a number of factors that govern the fertile to fissile conversion rate. We shall discuss as to how to maximize this rate and then attempt to match it with fissile depletion rate in the same reactor.

The integral fissile production rate in a reactor depends on the fertile inventory, flux level and effective capture cross-section of fertile isotope(s) for a given neutron spectrum. When fertile material does not contain any externally fed fissile seed, one can achieve the best fissile conversion rate. In a thermal reactor system if unseeded thorium can be loaded in large measure, one can achieve three times higher fissile production rate compared to uranium, due to the intrinsic difference in their capture cross-sections. The asymptotic fissile accumulation potential for thorium is nearly 14 g/kg of ^{233}U in thorium. The concentration of ^{233}U remains at this level for subsequent irradiation for a long time. In the fast reactor system seedless thorium and depleted uranium can both be considered for high fissile production rate. The asymptotic fissile (fresh seed) accumulation potential in a fast reactor system is nearly 100 g/kg for both thorium and depleted uranium. Loading of unseeded fertile material is normally practiced in fast reactors outside the active core in radial and axial blanket regions, where the absolute flux level seen by the blanket region would be three to six times lower than that in the active core region. Hence fissile depletion would occur at a much faster rate in comparison to fissile production rate in blanket regions.

It is advantageous to accommodate the seedless fertile material inside the core to achieve comparable flux values in the fissile seed and fertile zones. In order that these seedless fertile zones see uniformly high flux level, it is necessary to distribute them evenly in the entire core without clustering. A typical arrangement of accommodating seedless fertile zones between the fissile zones is schematically indicated in Figure 1.

In ATBR, loading of seedless thoria rods in high neutron flux ambience and use of the same rods for subsequent power generation are considered as the main distinguishing features *vis-à-vis* earlier work on thorium[12], where some externally fed fissile is normally considered.

Figure 2 shows a typical arrangement of the seedless thoria cluster. Loading of large volume/mass of fertile material without any seed is mandatory for enhancing the fissile production to be matched with fissile depletion. This would require much higher feed enrichment in seed fuel rods, since the rods not only produce fission power but also provide surplus neutron flux ambience for the neighbouring fertile (incore blanket) regions. In order that this process lasts for the longest possible duration, it is necessary to maximize the initial feed in the seed zone and somehow decrease the burning rate of the seed fuel rods. This can be achieved in a thermal reactor system by two means.

The seed fuel rods are deliberately chosen to be of thinner dimension with sufficiently large fissile content. With higher seed content, the flux level would decrease for a given power density. The effective absorption cross-section also would decrease due to self-shielding of fissile atoms. In addition, the seed fuel rods are surrounded by thoria rods so that they would receive a much diminished thermal flux from the moderator region outside. Typical arrangement of a seed fuel cluster is shown in Figure 3.

Boiling light water is used as coolant. Boiling H_2O does about 50% of the moderation as well. The pressure tube size is chosen to be much bigger than that of the Fugen or AHWR (ID of 176 mm as against 120 mm), so as to accommodate adequate number of thicker thoria rods in the outermost ring. The fuel cluster turned out to be a seven-ring cluster having 127 rods. In order to minimize power peaking within the cluster, the central four rings (37 rods) were replaced by a BeO block. The fuel cluster consists now of only two rings of thinner seed fuel rods surrounded by one ring of thick thoria rods. The thoria rod diameter is also chosen to be 26% larger. The coolant volume is also thereby minimized. This was also the way by which the LOCA (Loss of Coolant Accident) reactivity coefficient could be made nearly zero or negative[13].

Power mismatch between the seed fuel rods and fertile thoria rods is minimized in three ways. Thoria rods are chosen to be not fresh but one cycle-irradiated rods. They are supposed to be exposed in the same reactor in the previous cycle. The relatively complicated task of dismantling and re-fabricating, rather reconstituting, irradiated thorium fuel assemblies has also been suggested by others:

- Radkowsky's thorium reactor (RTR) concept[14] – where the central seed zone in each fuel assembly of one-third core is replaced annually, while the outer thorium fuel rods are replaced at a less frequent interval of nine years.
- The Advanced Candu Reactor (ACR) design[15] proposes reconstitution of irradiated thoria pins in each of the short length Candu-type fuel bundle of 50 cm length. There the task is obviously much more cumbersome.

In ATBR the engineering design of the fuel assembly should be made such that the two rings of fresh seed fuel rods are almost easily inserted into the irradiated thoria cluster ring – perhaps as is suggested in the RTR design.

Further, in ATBR, a batch fuel loading is preferred. A typical optimized five-batch fuelling scheme with 72 assemblies per batch considered earlier[3] is illustrated in Figure 4, where the colour scheme indicates the number of fuel cycles seen by a batch of fuel assemblies. In the later discussions we would give a three-batch fuelling scheme with 120 assemblies per batch, which could operate for two years.

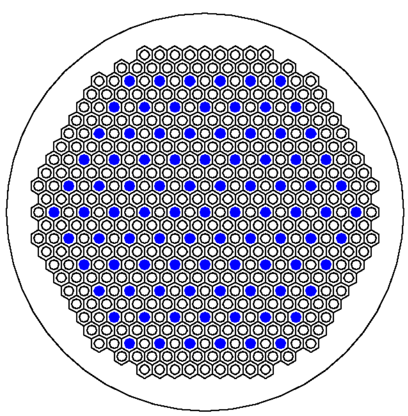

Figure 1. Uniform distribution of fertile zones amidst fissile zones. Shaded – Fertile blanket assemblies; Blank – Seed fuel assemblies.

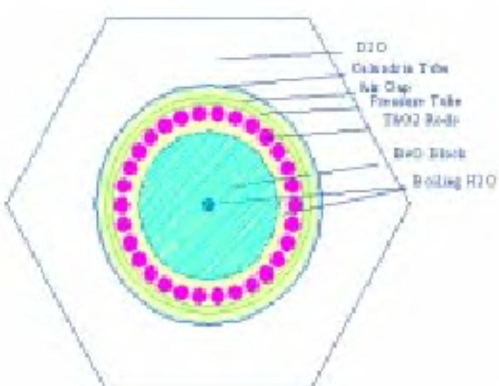

Figure 2. Typical arrangement of seedless thoria cluster.

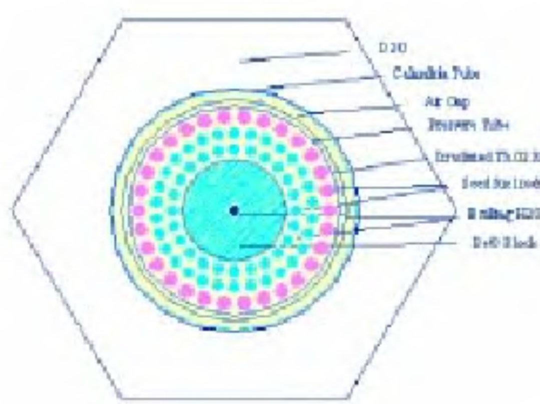

Figure 3. Typical arrangement of seed fuel cluster.

Table 1. ATBR core design parameters considered for Pu seeded core

Reactor power	MWe	600
	MWt	1875
Total core flow	(tonnes/h)	27,000
Average heat rating	(w/cm)	172 (neglecting thoria clusters)
No. of (ThO_2 + PuO_2) fuel clusters in the core		360
No. of natural ThO_2 clusters in the core		120 (fixed) + 25 (moveable) = 145
No. of fresh fuel assemblies per batch		120 (seeded) + 120 ThO_2 (no seed)
Active core height	(mm)	3600
Average fuel temperature	°C	600
Average coolant temp. (Boiling H_2O – 70 kg/cm^2)	°C	286
Coolant inlet subcooling	(kcal/kg)	7 to 20
D_2O – Moderator temperature	°C	80
Radial D_2O reflector thickness	(mm)	600 to 700
Axial D_2O reflector thickness	(mm)	600
Calandria tank size	(m)	~8.4 dia × 4.8 height
Control system		
Fast shutdown/^{233}Pa to ^{233}U after S/D		Injection of liquid poison in dry tubes. Stainless steel rods in inter-channel space.
Shutdown hold		Partial moderator dump during refuelling outages
Xenon over-ride		Movable ThO_2 clusters (25 nos)

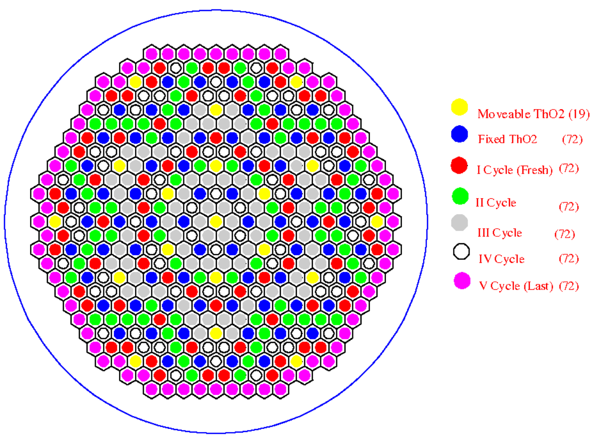

Figure 4. ATBR core 360 seeded + 91 thoria fuel clusters. Seventy-two assemblies per batch; Five-batch loading – optimized pattern.

Depending on the fuel cycle duration and location of thoria clusters in the core during their first cycle, they would contain nearly 60–70% of the asymptotic *in situ*-bred fissile content. Since they face the thermal flux directly from the moderator, the relative power factor in the thoria rods is found to be at least 0.5 to 0.6, when the seed fuel rods are fresh and contain nearly 15–20 times the fissile content. With burn-up, the power share of thoria rods steadily increases due to further fissile accumulation and near discharge burn-up it may even cross unity, i.e. the thoria rods which were initially receiving neutrons from the inner seed fuel would become the supplier of neutrons and also take the major share of power within the fuel cluster. It is necessary to reach such high burn-up when the crossover of power share-shift from seed to fertile thoria rods takes place, for the best physical characteristics like two-year cycle length with minimum external control manoeuvres. The Pu seed content was therefore chosen to be as high as 20 and 14% respectively, in the inner and middle ring of seed fuel rods shown in Figure 3. The diameter of the inner and middle fuel rods was chosen as 10 and 9 mm respectively while the diameter of outer thoria rods was chosen as 12.6 mm.

To summarize, the new type of reactor should consist of thin seed fuel rods of high feed enrichment serving as torch or fire to ignite the surrounding fertile breeding zones. The seed fuel would generate surplus neutrons in addition to power. These neutrons move about freely in certain flux traps created by vacating the seed fuel zones at regular intervals. The D_2O moderator is ideal for creating large thermal neutron flux traps. Unseeded thoria clusters should be placed in these flux traps to achieve high fissile conversion rates during the first cycle of the thoria clusters. The high fissile conversion is continued also in subsequent fuel cycles by placing the irradiated thoria clusters between fresh seed fuel rods and the D_2O moderator. Since thoria rods occupy the outermost ring to receive the major share of thermal neutron flux incident from the D_2O moderator region, they also shield the seed fuel rods so that seed would not rapidly deplete. The ratio of volumes of the fissile breeding zones and fissile depleting zones, rather their masses, is typically 50 : 50. A batch fuel-loading scheme with optimized loading pattern ensures that the thermal flux faced by every thoria cluster is fairly high and uniform. When this is accomplished, the core k_{eff} is maintained just above unity for as long as two years. In fact, there will be an increase of core excess reactivity up to the middle of the fuel cycle when the conversion rate in fresh thoria clusters is maximum and thereafter it tapers down slowly. Results of the fresh analysis for equilibrium fuel cycle of the conceptual reactor ATBR with PuO_2 seed are presented here. Reactor-grade Pu contains 24% of ^{240}Pu, which also helps in initial suppression of reactivity,

Table 2. Description of fuel clusters (seeded + unseeded)

	Fuel type			
	Seeded fuel cluster (Pu reprocessed from power reactors)			Unseeded ThO_2 cluster
Parameter	Inner	Middle	Outer	Single ring
Fuel clad ID/OD (mm)	10/11.4	9/10.4	12.6/14	12.6/14
Pitch circle dia (mm)	104	130	158	158
No. of fuel rods	24	30	30	30
Seed content (wt %)	20 PuO_2 in ThO_2	14 PuO_2 in ThO_2	One cycle irradiated ThO_2	Fresh unseeded ThO_2 rods
Fissile fraction in seed	0.745		>0.94	–
Composition of seed	(^{239}Pu : ^{240}Pu : ^{241}Pu : ^{242}Pu) :: (69.3 : 24.1 : 5.2 : 1.4)		0.5 to 0.7% *in situ*-bred ^{233}U	–
ID/OD of central BeO block (mm)		10/90 (inclusive of Zr-liner)		10/137
Pressure tube Zr–Nb (2.5%) ID/OD (mm)		176/187		176/187
Air gap ID/OD (mm)		187/204		187/204
Calandria tube Zr-2 ID/OD (mm)		204/207		204/207
Hexagonal assembly pitch (mm)		300		300

Note: Fissile fraction in seed is sum of ^{239}Pu and ^{241}Pu fractions.

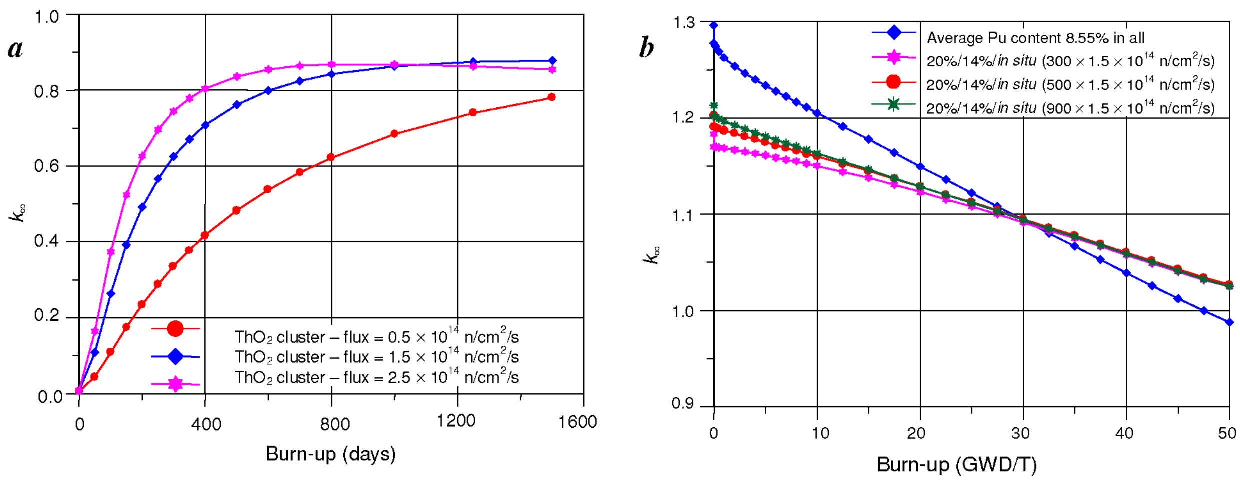

Figure 5 *a*, *b*. ***a***, k_∞ of thoria cluster after irradiation at different flux levels; ***b***, k_∞ of seed fuel cluster with different initial fluence levels for thoria rods.

and its conversion to ^{241}Pu also helps in maintaining flat reactivity with burn-up. Reactivity change (fall) is higher for other seeds like ^{235}U or ^{233}U[4].

Table 1 gives the design parameters of the ATBR core. A power level of 600 MWe or 1875 MWt is considered. The reactor considers vertical pressure tubes (PT) of Zr–Nb (2.5%) with ID/OD of 176/187 mm, at a hexagonal lattice spacing of 300 mm. Boiling light water coolant at a pressure of 70 bar is considered. The ID/OD of Zr-2 calandria tube (CT) is 204/207 mm, with an air gap separating the PT and CT. D_2O moderator is filled in the calandria tank of 8400 mm diameter and 4800 mm height at normal pressure and temperature of 80°C at hot operating state. This would provide a radial reflector of 600–700 mm thickness and axial reflector of 600 mm thickness at the bottom and top for a core height of 3600 mm.

Table 2 gives the description of the two types of ATBR fuel clusters. The seed fuel cluster consists of two rings of 24 and 30 seed fuel rods at pitch circle diameter (PCD) of 104 and 130 mm respectively. Thoria rods are at PCD of 158 mm. The pure thoria cluster contains only one ring of seedless thoria rods at PCD of 158 mm. There is a BeO block inside the above two types of clusters with OD of 90 mm and 137 mm respectively. This block serves to eliminate 37 inner fuel rods and to decrease local peaking within the seed fuel cluster. The seed fuel considers reactor-grade Pu with PuO_2 content of 20 and 14 w/o in the inner and middle rings. The Zr–Nb (1%) clad is 0.7 mm thick for all the rods. The engineering specifications and dimensional details given here have been worked out based on the characteristics of known LWRs world over. They can be fine-tuned on detailed engineering evaluations, if required.

Calculation model and results

The lattice calculations of ATBR fuel clusters are done using the CLUB module[16] of the PHANTOM code system[17]. The recent calculations have been performed by the IAEAGX library in 172 energy groups and in WIMS/D format. This nuclear data library was generated as part of IAEA CRP on WIMS library update project[7,8]. CLUB code solves the transport problem by collision probability method. First flight collision probability method is used within each macro ring region and three term expansion is used for angular currents at macro interfaces. The outer hexagonal boundary is cylindricalized.

The fertile thoria clusters are simulated first. Since it does not contain any external seed, the thoria cluster burn-up calculations are done at three typical one-group flux levels of (0.5, 1.5 and 2.5) $\times 10^{14}$ n/cm^2/s maintained constant and up to 1500 days of irradiation. The seed fuel clusters are then simulated with thoria rod isotopic densities picked up at fluence levels of 300, 500, 700 and 900 days at the above three flux levels. These are the typical expected cycle length durations. Figure 5 *a* and *b* shows the variation of k_∞ with burn-up for the thoria cluster and the seed fuel cluster for typical flux value of 1.5×10^{14} n/cm^2/s. It is seen that k_∞ of the thoria cluster rises sharply up to 800 days and then stays nearly flat. For the seeded fuel cluster the initial k_∞ is ~1.2 and is higher with higher starting fluence levels in thoria rods. The difference however narrows down with burn-up and it is noted that k_∞ remains above unity even up to an assembly average burn-up of 50 GWD/T. At this stage, the unseeded thoria rods also achieve the same burn-up as the seed fuel rods. For the sake of comparison, the k_∞ plot is given for a cluster with average Pu content of 8.55% in all the rods. It is seen that the k_∞ variation of the seed fuel with thoria rods of *in situ* fissile content is less by about 100 mk. For ^{235}U or ^{233}U seed, the k_∞ variation will be more. The relative power share in the three rings is plotted in Figure 6. It is seen that the thoria ring power is 0.7 initially and crosses unity at 50 GWD/T.

The local peaking is initially 1.32 and occurs at the middle ring. It monotonically decreases and falls below unity at 37 GWD/T. Thinnest fuel rods (9 mm dia) are used in this ring. The burn-up accumulation in the three fuel rings for starting fluence level of (1.5×10^{14} n/cm^2/s $\times$ 700 days) in thoria rods is shown in Figure 7. It is important to note that the cumulative burn-up in unseeded thoria rods is 54 GWD/T, when the assembly burn-up is 50 GWD/T. It is also interesting to note that the inner 20% Pu seeded rods just reach 51 GWD/T at this burn-up, while the middle ring with 14% Pu reaches 55 GWD/T. The thoria rods started at a burn-up of 10 GWD/T due to prior irradiation up to the above-fluence level. Thus at the time of discharge both the seeded and unseeded fuel rods are seen to reach the same high discharge burn-up of ~50 GWD/T.

The core calculations are done using the code TRISUL developed for the purpose[18]. TRISUL is a hexagonal 3D finite difference diffusion code with one mesh per assembly radially. The lattice parameter interpolation for obtaining the two group cross-sections of seed and thoria fuel clusters as a function of burn-up, void (steam fraction), flux history and fluence thereof, and the xenon and Doppler perturbations applied and the thermal hydraulic model used, are explained in detail elsewhere[18,19]. Power-void iterations are done to obtain steam formation profile consistent with the power profile.

Figure 8 *a* gives the burn-up distribution at BOC and EOC of optimized three batch loading in equilibrium core. One-sixth core with rotational symmetry is simulated. The average flux seen by the thoria clusters in the previous cycle is also a key parameter in deciding the cycle length of a reload pattern. We chose the 120 thoria clusters out of the total 145 clusters. These thoria clusters are chosen to be the ones with the highest flux history levels.

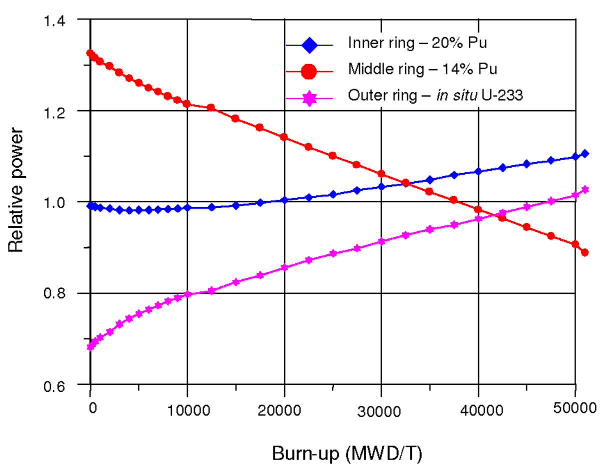

Figure 6. Relative power in each fuel ring for seed fuel cluster.

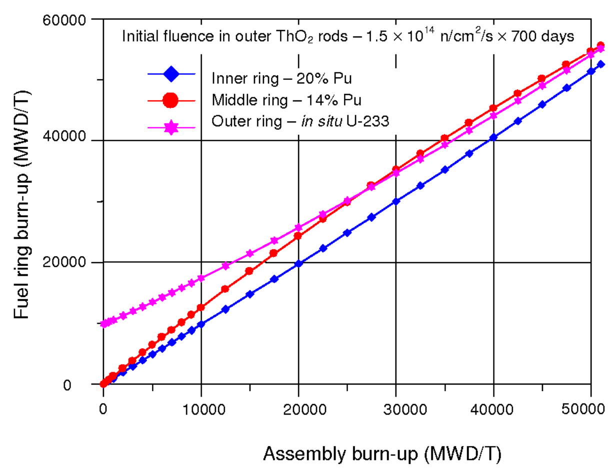

Figure 7. Burn-up accumulation in the three rings of seed fuel cluster.

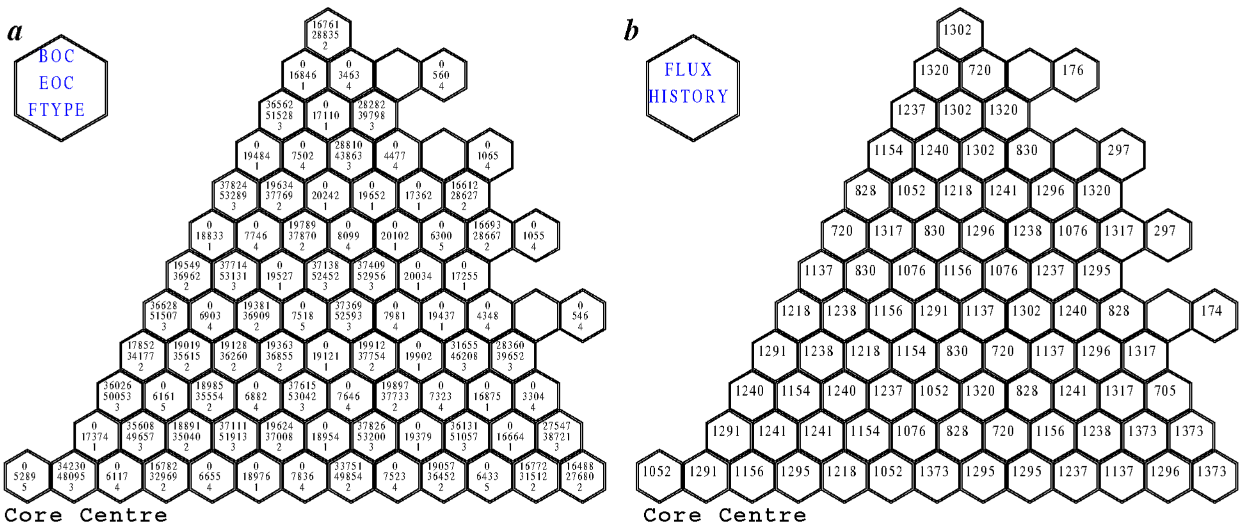

Figure 8 *a*, *b*. *a*, ATBR one-sixth equilibrium core 120 FAs per batch – BOC/EOC burn-up distribution (MWD/T). FTYPE: 1. (fresh) Cycle-1; 2. Cycle-2; 3. (last) Cycle-3; 4. Fixed thoria cluster; 5. Moveable thoria cluster. *b*, One-group absolute flux history values in units of 10^{11} n/cm^2/s (Core average value = 1.118×10^{14} n/cm^2/s) k_∞ of thoria cluster after irradiation at different flux levels.

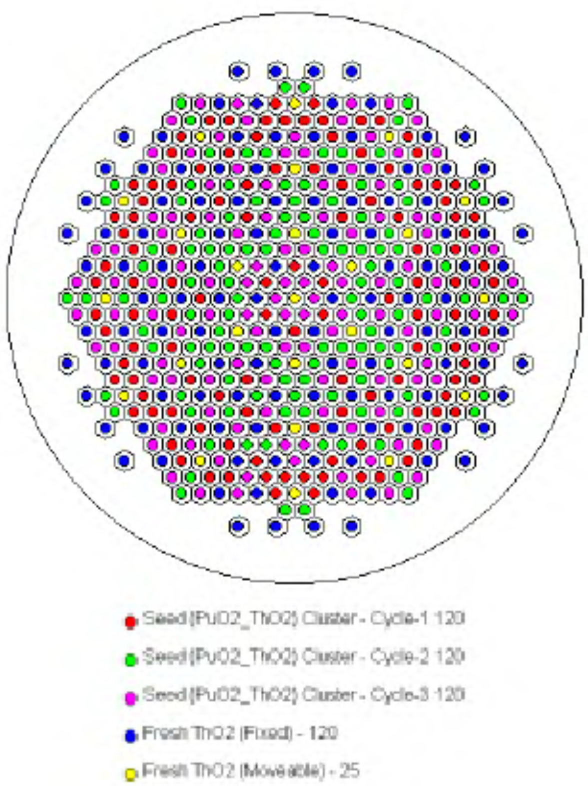

Figure 9. ATBR equilibrium core 120 FAs/batch – 720 EFPD. Schematic diagram of the three-batch fuels and thoria clusters.

Figure 8 *b* shows the absolute one-group flux history levels seen by the thoria clusters. The core average flux history is 1.118×10^{14} n/cm^2/s. For interpolation of cross-sections, three-dimensional distribution of flux history and fluence thereof is considered. Since the cycle length achievable was seen to be 720 days, the seed fuel clusters consider the thoria rod fluence to be the product of the respective flux history level and 720 days. Longer cycle length and higher fluence also tacitly increase the fissile inventory in equilibrium core through the *in situ* production of ^{233}U in the same core in previous cycles. Fresh seed fuel clusters are avoided at core periphery locations. This is to enable a low leakage loading pattern. Figure 9 shows a schematic diagram of the three-batch fuelling scheme. This scheme is normally more difficult to optimize in comparison to the five-batch fuelling scheme shown in Figure 4. The variation of k_{eff}, and peaking factors as a function of core burn-up are shown in Figure 10 *a* and *b*. The k_{eff} increases from 1.0212 at BOC to 1.0265 at 390 FPD and then decreases to 1.0187 at EOC. Increase of k_{eff} up to 390 days shows the thorium breeding phase – hence the name thorium breeder.

A variation of ± 4 mk over a period of two years would require minimal control management and can be partly met by coolant inlet enthalpy variations or small movement of moveable thoria clusters. Figure 11 *a* gives the radial power distribution at BOC, 360 FPD (MOC) and 720 FPD (EOC). Figure 11 *b* gives plots of axial power profile at these burn-up values. It is seen from Figure 10 *b* that 3D power peaking monotonically decreases from 1.72 to 1.26. The radial and axial peaking factors also decrease monotonically.

3D flux plots at core mid plane at BOC and EOC are given in Figures 12 *a*, *b* and 13 *a*, *b* for epithermal and thermal energy groups. It is seen that the epithermal flux shows depression in thoria clusters, which appears as mounds in thermal flux plots. Thus excess neutrons produced by the seed fuel rods slow down and create thermal flux traps for effective breeding in the thoria cluster locations.

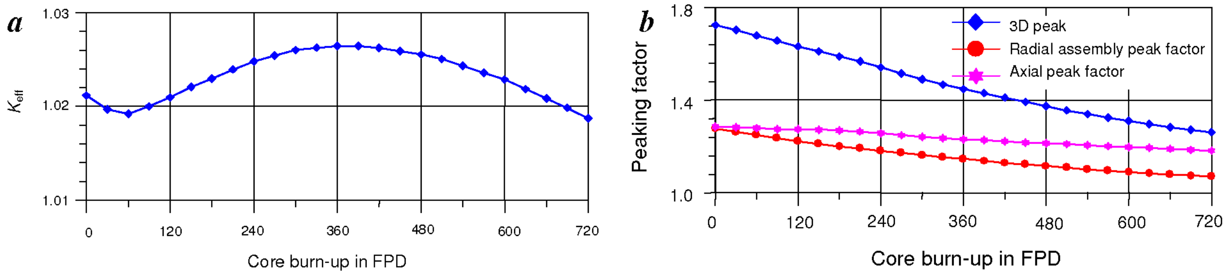

Figure 10 ***a***, ***b***. ***a***, ATBR equilibrium core 120 FAs/batch–720 EFPD – k_{eff} vs cycle burn-up in FPD; ***b***, Peaking factor vs cycle burning in FPD.

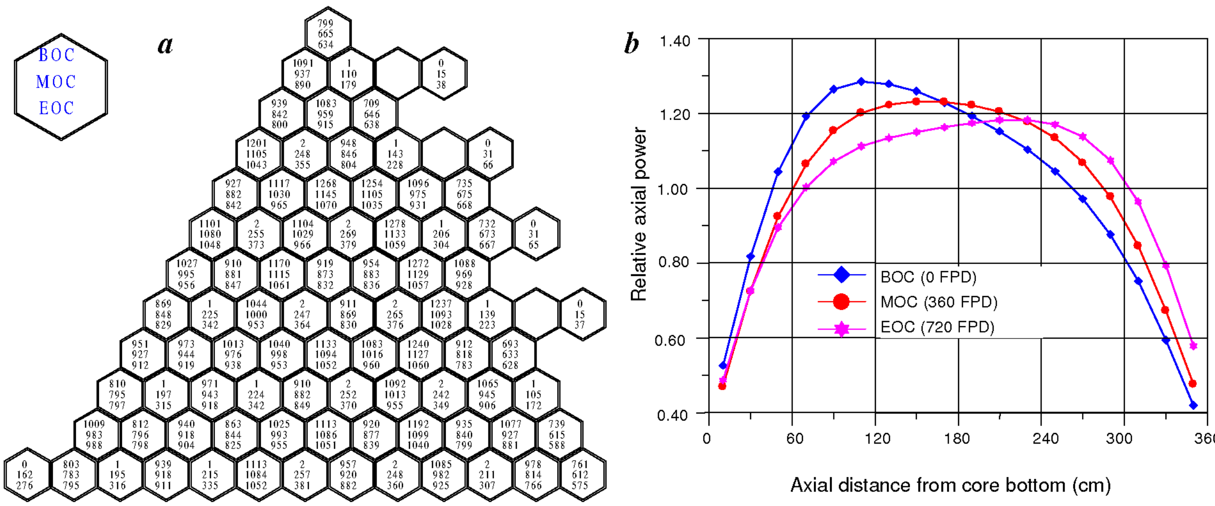

Figure 11 ***a***, ***b***. ***a***, ATBR one-sixth equilibrium core 120 FAs/batch–radial power distributions at BOC/MOC/EOC. The radial power distribution given here is relative power in each fuel assembly. They are multiplied by 1000 to print in integer format. A value of 1000 means it is average relative power = 1.0. BOC/MOC/EOC, Beginning/middle/end of fuel cycle. ***b***, ATBR-600 equilibrium core with PuO_2 seed in ThO_2. Axial power distribution at BOC/MOC/EOC.

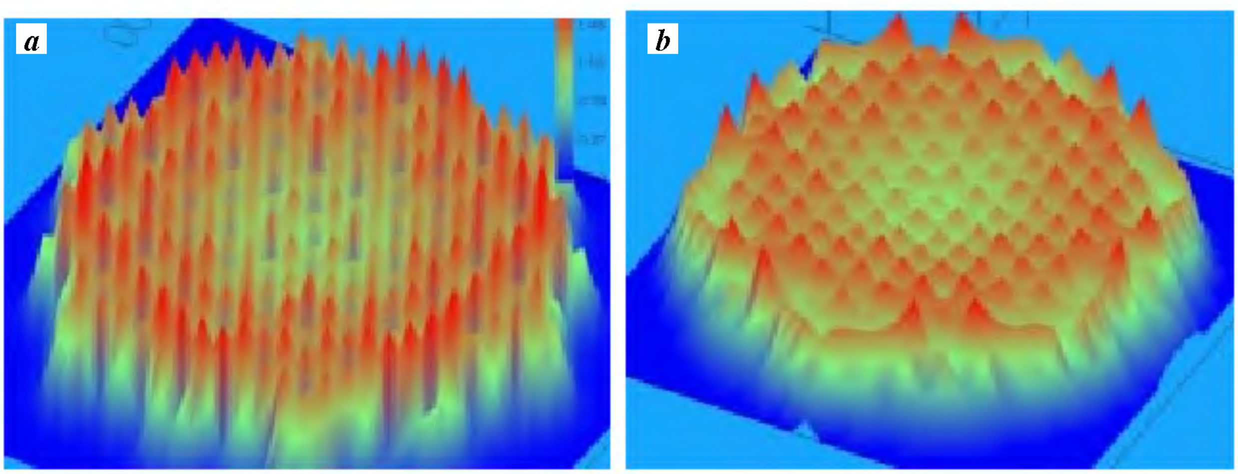

Figure 12 ***a***, ***b***. ***a***, ATBR-600 equilibrium core with PuO_2 seed in ThO_2–epithermal flux distribution at BOC–0 FPD; ***b***, Thermal flux distribution at BOC–0 FPD.

Table 3 gives the seed input and output contents for the equilibrium core. It is seen that only 40% of the Pu feed is consumed (0.88 out of 2.2T). Since thoria rods achieve about 50 GWD/T burn-up, nearly 640 kg of 12.78T of thorium loading (at the rate of 50 kg/T) in the unseeded thoria rods is used for energy production in its four fuel cycle operation. About 502 kg of uranium is available from the discharged thorium with 87% fissile. This shows that

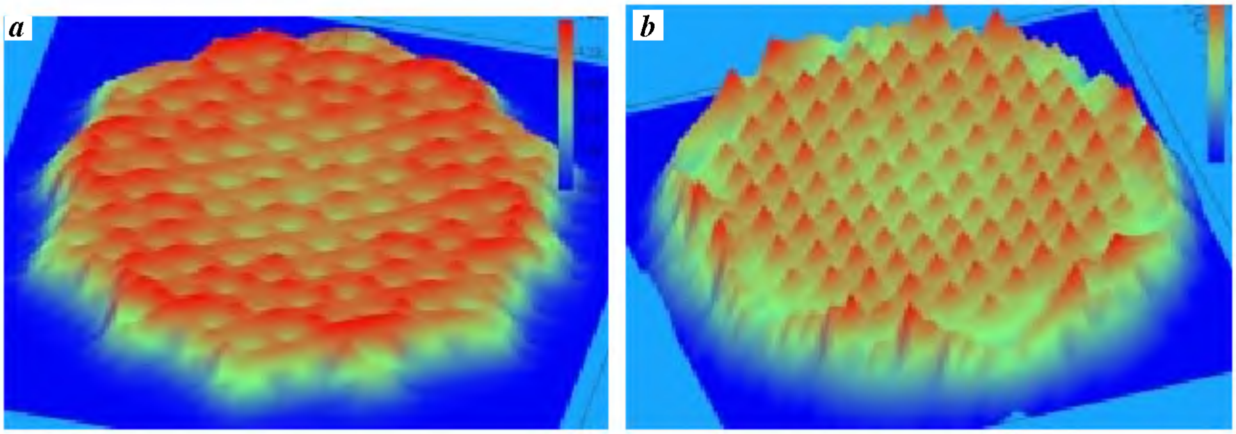

Figure 13 *a*, *b*. *a*, ATBR-600 equilibrium core with PuO_2 seed in ThO_2–epithermal flux distribution at EOC–720 FPD; *b*, Thermal flux distribution at EOC–720 FPD.

Table 3. Summary of the equilibrium core studies

Parameter	Results with IAEAGX-172 group library
Average discharge burn-up (MWD/T)	49050
Pu seed input in fresh batch of 120 assemblies (kg)	2212.1
Fissile Pu content (kg)	1647.4
Fissile fraction (%)	74.5
Seed output in discharged batch (kg)	1834.5
Output-to-input ratio	0.829
Break-up of seed output	
Weight of U-total in thorium (kg)	502.3
Weight of ^{233}U in thorium (kg)	426.3
Weight of $^{233}U + ^{235}U$ in thorium (kg)	436.9
Fissile fraction (%)	87.0
Weight of total Pu in thorium (kg)	1332.2
Weight of fissile Pu (kg)	731.4
Fissile content in output (kg)	1168.3
Fissile fraction (%)	63.7
Core reactivity at full power	
Minimum reactivity (mk)	18.4
Maximum reactivity (mk)	25.8
Reactivity spread (mk)	7.4 or ± 4
Void reactivity coefficient ($\partial\rho/\partial v$) in (mk/%void)	–0.32 (BOC)
(Core average void changed from 24.6 to 60%)	–0.08 (EOC)

Pu seeded core; three-batch fuelling; 120 assemblies per batch; cycle length – 720 EFPD.

886 kg of reactor-grade Pu is utilized for converting 1142 kg of thorium to uranium, of which 640 kg is used to produce 50% share of power in the same reactor. Thus ATBR can be used for Pu incineration and it produces intrinsically proliferation-resistant ^{233}U. Since 50% of the core loading is always unseeded thorium, the load on reprocessing and refabrication of back-end fuel will be proportionately less.

It must also be added that the conversion ratio of 0.83 achieved for the ATBR–600 MWe power reactor is one of the highest values (albeit theoretically), higher than that of any operating thermal power reactor (0.6 for LWR and 0.7 for PHWR). The above ratio is more if the fissile ^{233}U formation in additional 25 thoria clusters in ATBR is taken into account. By cutting down the fuel burn-up, this ratio could be increased further. But it is not economical to foreclose a fuel cycle which is capable of running for much longer duration from reactivity potential consideration. Since the control absorber inventory at rated power operation is nearly eliminated in the ATBR, the ATBR fissile conversion can be regarded as one of the best. We had reported the comparison of eUO_2, Pu, ^{233}U seeds in our earlier work[4]. With ^{233}U, we obtained a seed output-to-input ratio of 0.93.

In addition, it is important to note that the seedless thoria rods also achieve a high discharge burn-up of 50,000 MWD/T, almost equal to that of Pu-seeded rods. This energy production has come from *in situ* conversion of ^{232}Th to ^{233}U and utilization of ^{233}U in the same reactor for energy production.

The void perturbation was evaluated by decreasing the flow and also the inlet subcooling at the full reactor power. The reactivity change when the core average void changes from 0.246 to 0.6 is –0.32 mk/% void at the beginning of the cycle and –0.08 mk/% void at the end of cycle of equilibrium core. These results are comparable to the earlier results obtained with 69 group WIMS libraries[5].

Conclusion

The ATBR core design with Pu seed in thorium is found to exhibit excellent core characteristics like two-year cycle length with practically no control manoeuvres. This is achieved using thin seed fuel rods with high Pu content to create large volumes of neutron flux trap zones, where the fertile breeding in thoria rods can take place at a rate matched with fissile depletion rate. The fissile seed remains conserved for a long duration of six years (three fuel cycles) due to its location in the fuel cluster. The seed and fertile fuel rods achieve the same high discharge burn-up of ~50 GWD/T. The reactivity coefficients are found to be small. The coolant void coefficient in the operating range is negative. This ATBR core with Pu seed has an overall safe and economic characteristics. Longer cycle length is also desirable in closed fuel cycles to maximize the time gaps needed for reprocessing and refabrication. The ATBR with Pu feed can be regarded as a Pu incinerator and it produces the intrinsically proliferation resistant ^{233}U for sustenance of future reactor programmes. Since 50% of the core loading is always unseeded thorium, the load on reprocessing and refabrication of back end fuel will be proportionately less. It can also be designed for burning minor actinides, since it is designed to accommodate large fertile breeding zones.

When ^{235}U gets exhausted, there is no alternative to Pu as the sole means of sustaining the nuclear power. This will happen sooner in countries having limited uranium reserve. Use of Pu to produce large amounts of ^{233}U is advantageous for extending the thermal power reactor programme. ^{233}U is regarded as a better proliferation resistant material due to the ^{232}U content, which gets accumulated to several hundreds of ppm level. ^{232}U has relatively low half life of 72 years and the daughter products of ^{232}U are hard gamma emitters.

The delayed neutron fraction β is 2.5 to 3.2 mk in the Pu-seeded core and prompt neutron mean life time is ~10–15 μs. The kinetics behaviour of the ATBR core would be similar to fast reactors using Pu feed. However, since all reactivity coefficients are small in magnitude and minimum control manoeuvres will be needed it is expected that the operation of ATBR can be smooth and stable. The initial core and approach to equilibrium core loading, control design and stability characteristics are being studied.

Long fuel cycle length of two years with no external absorber management or control manoeuvres does not exist in any operating reactor. Small magnitude of reactivity coefficient makes the ATBR design intrinsically safe. High seed output-to-input ratio contributes to good fuel economy.

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