# A THORIUM BREEDER REACTOR CONCEPT FOR OPTIMAL ENERGY EXTRACTION FROM URANIUM AND THORIUM

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## Abstract

An attractive thorium breeder reactor concept has been evolved from simple physics based guidelines for induction of thorium in a major way in an otherwise enriched uranium reactor [1]. $D_2O$ moderator helps to maximise reactivity for a given enrichment. A relatively higher flux level compared to LWRs offers the advantage of higher rate of $^{233}U$ production in thoria rods. Thus fresh thoria clusters consider no feed enrichment. In an equilibrium core, a full batch of pure thoria clusters are loaded during each fuel cycle. They undergo irradiation for about one year duration. By this time they accumulate nearly 70% of the asymptotic stable concentration of $^{233}U$, if they face a flux level of the order of $10^{14}$ n/cm$^2$/sec. In the next fuel cycle, these thoria rods in ring cluster form are juxtaposed with the fresh enriched fuel rods, also in ring cluster form. Such integrated fuel assemblies are then irradiated for four or five fuel cycles, at the end of which U as well as Th rods attain a reasonably high burnup of about 30-32 MWD/kg. The core characteristics are quite attractive. The core excess reactivity remains low due to large thoria inventory which makes the net burnup reactivity load to be below 1%. The core is capable of being operated in an annual batch mode of operation like a LWR. The control requirement during power operation is negligible. Xenon over-ride requirement is low and can be managed by partial withdrawal of a few thoria clusters. Void reactivity is nearly zero or negative by the optimum design of the fuel cluster. Reactivity changes due to temperatures of fuel, coolant and moderator are also small.

## 1. INTRODUCTION

For generation of fission nuclear power both uranium and thorium have comparable gross energy potential. The present day nuclear reactors use mainly uranium because one needs some external feed enrichment for thorium, while it is intrinsically present in uranium. This paper explores the possibility of avoiding such feed enrichment. It is conjectured that if thoria rods are placed like control clusters in a thermal reactor using enriched fuel, and are allowed to face a fairly large flux of the order of $10^{14}$ n/cm$^2$/sec, they would accumulate significant $^{233}U$ in one fuel cycle. Subsequently they can be used as fuel rods along with normal fresh enriched fuel rods and irradiated for four or five more fuel cycles. The physics based guidelines to evolve the new reactor concept are enumerated in Ref.1. They can be briefly summarised as follows.

- $D_2O$ moderator is necessary to enhance the reactivity as well as the flux level incident on thoria rods.
- A fairly large sized fuel cluster with lattice pitch less than the optimum ensures that the coolant void coefficient is near zero or negative. The moderation role is shared by inchannel hot coolant (boiling $H_2O$) and the outchannel cooler moderator $D_2O$.

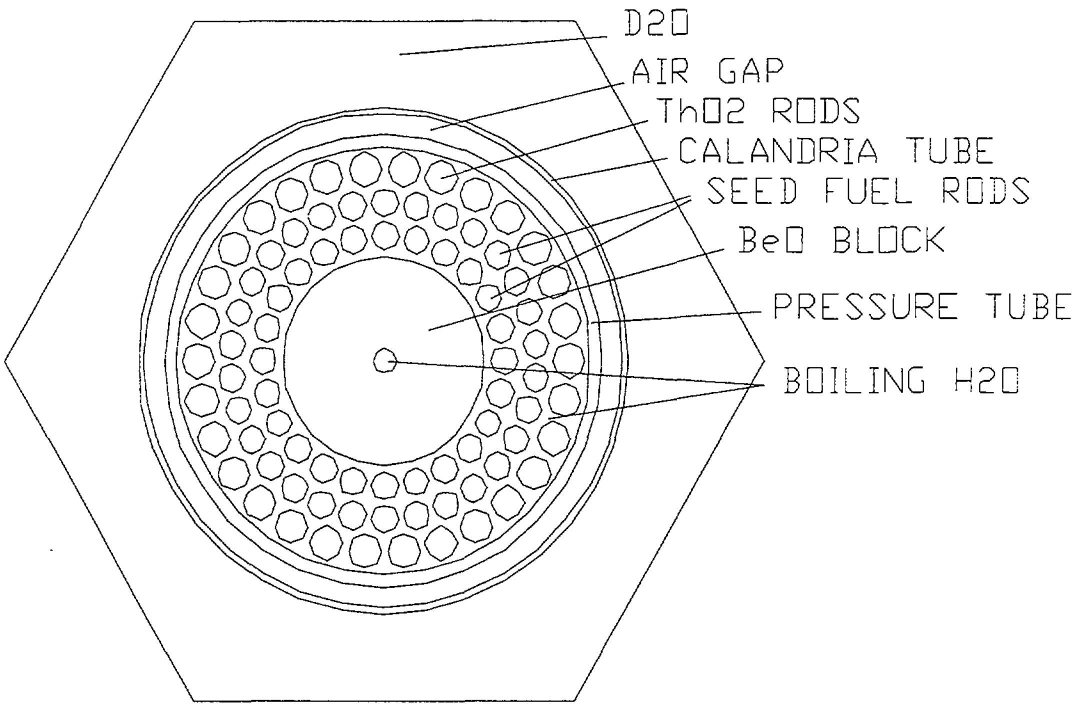

Fig. 1 84 Rod Cluster Fuel Assembly of the Proposed Thorium Breeder Reactor

**Table-1 Core and Fuel Design Parameters**

| | | | |
|---|---|---|---|
| Reactor Power | 1875 Mwt (600 Mwe) | | |
| Total core flow (tonnes/hr) | 27 X $10^6$ | | |
| Average heat rating (w/cm ) | 160 | | |
| Height of the core (cm) | 360 | | |
| No. of rods in a fuel cluster | 84 (54 seed rods + 30 $ThO_2$ fertile rods) | | |
| No. of rods in pure thoria cluster | 30 $ThO_2$ | | |
| No. of fuel clusters in the core | 360 | | |
| No. of pure thoria cluster in the core | 72 (varied from 72 to 90) | | |
| Ring → | Inner | Middle | Outer |
| No. of rods | 24 (seed) | 30 (seed) | 30 (fertile) |
| Enrichment | see Table-2 | see Table-2 | insitu |
| Pitch circle dia (cm) | 10.4 | 13.0 | 15.8 |
| Clad ID/OD (cm) | 1.0/1.14* | 1.0/1.14* | 1.26/1.40 |
| Clad Material | Zr-Nb(1%) | Zr-Nb(1%) | Zr-Nb(1%) |
| Assembly Lattice Pitch (hexagonal) (cm) | 30 (32 cm also used for 'eueut' fuel) | | |
| Average Fuel Temperature | 600°C | | |
| Average Coolant Temp. (Boiling $H_2O$ - 1015 psi) | 286°C | | |
| Central Moderator Block | BeO | | |
| ID/OD (cm) | 1.0/9.0 (inclusive of Zr-liner) | | |
| Pressure Tube (PT) Zr-Nb (2.5%) ID/OD (cm) | 17.6/18.70 | | |
| Calandria Tube (CT) Zr-2 ID/OD (cm) | 20.40/20.70 | | |
| Moderator Material/Temperature | $D_2O$ - 80°C | | |
| Additional locations for Shutoff Rods | 7 | | |
| Radial $D_2O$ reflector thickness (cm) | 60 to 70 | | |
| Axial $D_2O$ reflector thickness (cm) | 60 | | |
| Calandria Tank Size | ~8 m dia X 4.8 m height | | |

* For seed type 'tptpt' thinner fuel dia was considered.

**Table-2 Description of Seed Zones**

| Fuel Type | **eueut** | **npnpt** | **nunut** | **tptpt** | **tutut** |
|---|---|---|---|---|---|
| Seed zone | enriched $UO_2$ | $PuO_2$ in nat. $UO_2$ | $^{233}U$ in nat.$UO_2$ | $PuO_2$ in $ThO_2$ | $^{233}U$ in $ThO_2$ |
| Fuel Pellet Dia (mm) | 10 | 10 | 10 | 9 | 10 |
| Seed content in inner ring | 4.5% $^{235}U$ | 9% Pu (74% fissile) | 3.3% (92% $^{233}U$) | 10% Pu (74% fissile) | 4.9% (92% $^{233}U$) |
| Seed content in middle ring | 3.6% $^{235}U$ | 5% Pu (74% fissile) | 2.6% (92% $^{233}U$) | 6% Pu (74% fissile) | 3.9% (92% $^{233}U$) |

The reactor is akin to that of a SGHWR (Steam Genearting Heavy Water Reactor). Fig.1 gives the schematic diagram of the proposed reactor fuel cluster. Table-1 gives the description of the core and fuel design parameters. The fuel can be briefly described as follows: There are three rings of fuel rods in a fuel cluster. Inner 24 rods and middle 30 rods constitute the seed zone. The outermost ring of 30 thoria rods is the fertile zone. As mentioned earlier, these fertile rods undergo prior irradiation for one fuel cycle duration and then only they are integrated with the fresh seed rods. BeO block with Zr-liner is used as filler material within each fuel cluster. This helps to achieve a low value of power peak within the fuel cluster. Pure thoria clusters contain only 30 $ThO_2$ rods and hence will need bigger BeO blocks as filler material. It is necessary to minimise the water volume to a bare minimum value in the core as well as in axial reflector zones in order to gain reactivity and also to reduce axial power peak.

In this paper, the potential of the proposed reactor concept for long term fuel cycle strategies involving a variety of seed zones is also briefly explored. Reprocessed $^{233}U$ or Pu as feed enrichment in either natural $UO_2$ or $ThO_2$ are conceived as the seed zones in addition to $^{235}U$ enriched $UO_2$ fuel. These 5 types of seed zones are described in Table-2. The outer ring of 30 $ThO_2$ fuel rods is common to all types and is vital for realisation of a possible thermal breeder.

The lattice calculations were performed with the CLUB module [2] of the PHANTOM code system [3]. 69 group WIMS cross section library was used. The core is assumed to have a hexagonal lattice structure.

For core calculations, a new core followup code TRISUL (Thorium Reactor Investigations with Small Uranium Loading), has been developed. This code is an extension of the TRIHEX-3D code [4] which uses few group diffusion theory and finite difference method with hexagonal or triangular meshes. TRISUL is a coupled neutronics cum thermal hydraulics code. Approximate thermal hydraulics calculations are done with the models which are used for Tarapur BWR square fuel assembly geometry.

## 2. RESULTS AND DISCUSSIONS

Preliminary investigations were done for all the five types of seed zones with TRIHEX-3D code. In order to compare the overall core characteristics, a flat zone-wise burnup model, typical average void value and a mean flux level for thoria clusters were assumed. The last parameter is crucial because the reactivity characteristics of the core are strongly influenced by the flux level prevalent in thoria assemblies and the integrated fluence achievable in their first fuel cycle of irradiation.

The observations from the above coarse studies are : The burnup reactivity swing is small (<1%) in all cases. The reactivity load of 72 pure thoria clusters is found to be ~9% at BOC and about ~5% at EOC for seeds 'eueut', 'nunut' and 'tutut'. In case of seed materials 'npnpt' or 'tptpt' the worth of thoria clusters is lower by 1%. A discharge burnup of 35,000 MWD/T is possibly achievable in all cases.

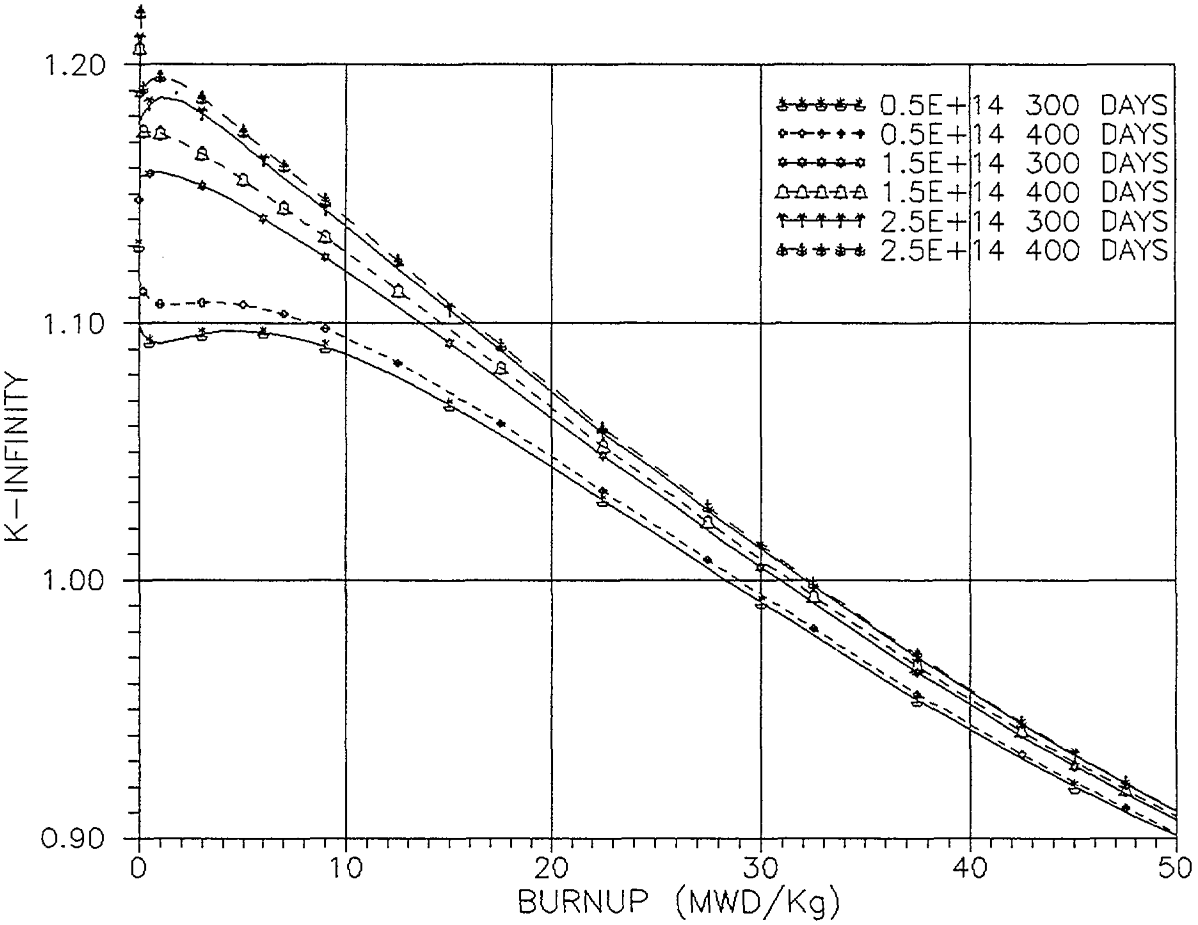

FIG.2 K-INF vs BURNUP OF 'EUEUT' FUEL WITH ThO2 RODS OF DIFFERENT FLUENCE LEVELS

**Table-3 Results of Core Follow-up Study with TRISUL for Core with 'eueut' Seed 78 Fuel Assemblies per Batch - $^{235}$U enrichment - 4.7% and 3.8%**

| Full Power Days | Core Average Burnup GWD/T | Core Average Void Fraction | $K_{eff}$ | Reactivity mk | Peaking factor |
|---|---|---|---|---|---|
| 0 (BOC) | 10.912 | 0.285 | 0.996379 | -3.63 | 2.184 |
| 50 | 11.743 | 0.285 | 0.993944 | -6.09 | 2.273 |
| 100 | 12.580 | 0.281 | 0.993484 | -6.56 | 2.292 |
| 150 | 13.427 | 0.276 | 0.993224 | -6.82 | 2.294 |
| 200 | 14.285 | 0.279 | 0.992936 | -7.11 | 2.252 |
| 250 | 15.153 | 0.282 | 0.992282 | -7.78 | 2.193 |
| 300 (EOC) | 16.031 | 0.282 | 0.991090 | -8.99 | 2.133 |

At the time writing this paper, detailed calculations were performed with TRISUL code for only one of the seed zones, viz., 'eueut'. For this fuel, a complete two group database was generated as a function of burnup at four void fractions, three flux levels (0.5, 1.5 and 2.5 X $10^{14}$ n/cm$^2$/sec), and irradiation duration of 300 or 400 days. Pitch was increased to 32 cm. Fig.2 shows the reactivity variation with burnup for 40% void and different fluence levels of thoria rods. It is seen that one can gain reactivity either by having higher flux level in thoria rods or by having longer time of irradiation.

**Table-4 Comparison of Fuel Requirement for 10 Gwe and 30 years Core Lifetime (Approximate Estimates for Relative Comparison)**

| Parameter | eueut | npnpt | nunut | tptpt | tutut |
|---|---|---|---|---|---|
| Discharge Burnup (MWD/T) | 35000 | 35000 | 35000 | 35000 | 35000 |
| Fissile feed per year (kg) | 388 | 727 | 349 | 689 | 378 |
| Specific power (kg/Mwe) | 0.65 | 1.21 | 0.58 | 1.15 | 0.63 |
| Fuel per 10Gwe, 30years (T)<br>300 efpd per year | 4845 U<br>3835 Th | 4845 U<br>3835 Th | 4845 U<br>3835 Th | ----<br>7356 Th | ----<br>8180 Th |
| Gross seed input* (T) | 194 | 363 | 175 | 344 | 189 |
| Gross Output Pu (T) | 39 | 198 | 39 | 117 | -- |
| U-233 (T) | 58 | 58 | 78 | 95 | 147 |
| (U-234, U-235 & U-236) (T) | 76 | 26 | 46 | 14 | 47 |
| Gross Output (T) | 173 | 282 | 154 | 226 | 194 |

* Seed includes $^{235}$U or ($^{233}$U, $^{234}$U and U$^{235}$ U) or ($^{235}$U and Pu isotopes), as applicable.

For the core analysis, several batch sizes were tried. Sample results are presented for the case of 78 fuel assemblies per batch. Table-3 gives the $K_{eff}$, overall power peak variation with burnup for an equilibrium core. It must be mentioned that that in this study all the thoria clusters were kept IN throughout the fuel cycle and no external reactivity control change was done, i.e. there was neither soluble boron adjustment nor any control device movement. It is seen that the fall in $K_{eff}$ is only 0.54%, though the $K_{eff}$ value is less than unity throughout the fuel cycle. Since the thoria clusters were kept IN all the time the small reactivity requirement of about 1% can be easily met by partial withdrawal of the thoria clusters. The latter can also be used for reducing the power peaking factors. Care must be taken to see that the integrated fluence in the thoria clusters remain adequate for adequate accumulation of $^{233}$U in them to provide adequate reactivity later.

The average absolute flux level in thoria clusters was seen to be only about $1X10^{14}$ n/cm$^2$/sec, though the flux level in surrounding zones is nearly double this value. This is due to the fact that fast flux drops by a factor of three in thoria cluster cells, while thermal flux is of similar magnitude in comparison to the neighboring cells. Thus it is necessary to enhance the fast or epithermal flux in thoria clusters. A small initial fissile content of 0.3% U$^{233}$ in all thoria rods, or better, 1.5-2% $^{233}$U in just 6 of the 30 rods in pure thoria cluster, or an inner nat. $UO_2$ rods fuel ring cluster, can help to mitigate the (fast) flux depression in thoria clusters and thereby ensure accumulation of adequate $^{233}$U in one year irradiation. Use of Be rods around thoria clusters can also augment the fast flux. The overall engineering feasibility has to be assessed. Pressurized $D_2O$ coolant can also result in higher flux level. Since burnup reactivity swing is small, there would be least movement of control and hence a deliberate higher power rating can also help in achieving higher flux level in thoria rods.

We compare in Table-4 the estimates of fuel requirement of the proposed reactor concept for installed capacity of 10 Gwe and a life-time of 30 years and 300 effective full power days (efpds) of operation per year. From Table-4 it is seen that use of $^{233}$U is superior to $^{235}$U as seed material as expected. This advantage will be slightly offset when $^{234}$U content increases after multi-recycling. When $^{233}$U is used along with natural $UO_2$ (nunut) one requires the minimum gross fissile input. When used with $ThO_2$ (tutut), slightly more fissile input is required, but the U$^{233}$ output is the largest in this case. If additional breeding in blanket type zone is also exploited, this option can become a net breeder of fissile material. When Pu is used as seed material, the gross seed input is nearly doubled. A large fraction of this material is discharged as unburnt Pu. This is due to large $^{240}$Pu content in Pu and high capture to fission ratio of Pu isotopes. The fissile content in Pu output is 70% while in U output it is above 90% ($^{233}$U).

## 3. UNCERTAINTIES IN THE CALCULATIONS

The calculations presented in this paper are of indicative nature only. There is bound to be uncertainty in the calculations due to the basic nuclear data available with the author(s). Calculational tool like TRISUL and the burnup model for studying a dynamic mixture of fresh seed and irradiated fertile zones is novel and needs testing. Nonetheless the physics based ideas expressed here point to a definite feasibility of the proposed concept with some minor revision of the design parameters.

## 4. CONCLUSION

The proposed thorium breeder reactor opens up the possibility of inducting thorium into an otherwise enriched uranium reactor. The overall core characteristics with respect to safety, operational ease and economy are seen to be attractive. The seed material, 'tutut', is quite attractive to enable not only self-sustaining mode of Th-$^{233}$U fuel cycle, but a steady growth would be feasible, if its breeding potential is properly exploited. However a proper mix of 'nunut', 'npnpt' and 'tutut' combinations should be worked out to exploit the energy potential uniformly from uranium and thorium. The overall Pu production and its accumulation can be minimised by using the 'npnpt' and 'tutut' seed types in the ratio in which these seed materials are regenerated.

## REFERENCES

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