THORIUM PRE-BREEDER/BREEDER ROUTE TO WIDEN THE NUCLEAR MATERIAL BASE FOR GENERATION OF ELECTRIC POWER*

V. JAGANNATHAN
Theoretical Physics Division,
Bhabha Atomic Research Centre,
Mumbai, India.

Abstract. Fission nuclear power is generated almost exclusively from uranium in the power reactors operating in the world today. Though the potential of thorium had been recognized very early, no cost-effective reactors have been designed that can use thorium in a major way. Eventually depleted uranium and thorium would become comparable candidates in the sense that both would need some man-made fissile isotope to continue fission nuclear power. Plutonium will be the only seed material that would be available from the fuel discharged from uranium reactors. In this paper an early induction of thorium in uranium reactors is advocated in order to widen the nuclear material base for continuation of fission nuclear power.

INTRODUCTION

The energy need has grown at a phenomenal rate in the 20th century. While the energy consumption rate has already reached its peak in the developed nations of the West, it is slated for similar such growth in rest of the world in the 21st century. Use of conventional fossil fuels like coal, oil and natural gas for meeting these energy needs is rather easier since the technologies for the same is proven. However, the fossil fuel resources are unevenly distributed and are limited. In addition, it is recognized that the emission from the burning of the fossil fuel leads to the Green House effect and the phenomenon of Global Warming. It would therefore be prudent to conserve these fossil fuels for the purpose of transportation and other domestic uses. It is necessary to look for alternative means of electricity production that would be eco-friendly and can last for several centuries to come.

In this context, energy from nuclear fission can be considered as a timely boon to mankind. Despite the two moral shattering accidents of Three Mile Island and Chernobyl, the fission nuclear power reactors can be deemed to have reached a high level of sophistication. They are capable of being operated with a degree of simplicity equal to or even better than the thermal power stations using fossil fuel. The amount of nuclear waste, especially in a closed fuel cycle, is much smaller in volume and is contained. Technologies are constantly being developed and improvised for its long term storage and disposal. Notwithstanding the apprehensions of the not so knowledgeable public or even the elite class, the nuclear power is likely to be pursued far more vigorously in the next century especially by countries with limited possibility of energy growth from fossil fuels.

It is noted that the present day power reactors use uranium almost exclusively. Thorium is not inducted in any major way since no cost-effective reactors have been designed. Introduction of thorium directly in the existing power reactor designs poses problems of reactivity load adjustment, disruption of power distribution etc. These problems manifest themselves in some form of economic penalty and hence use of thorium is not earnestly pursued by all countries. It is possibly necessary to conceive a new reactor system that is tailor-made for thorium, taking into account the factors like economy, safety and operation etc. India has a special interest in developing new reactor concepts suitable for large scale utilization of thorium, since its thorium reserves are six times that of uranium reserves.

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The physics disadvantages of thorium inhibiting its early use in power reactors are: i) thorium has no intrinsic fissile content, ii) the thermal absorption cross section of ^{232}Th, is nearly three times that of the fertile ^{238}U in uranium. A thorium breeder reactor (ATBR) concept was conceived in which these disadvantages were turned into advantages [1-6]. A conceptual design of a 600 MW(e) reactor was described in the above references. This reactor concept envisages essentially two phases. In phase-I, it is a pre-breeder, i.e., an efficient ^{235}U to ^{233}U converter. Phase-II will be a breeder or at least a self-sustaining reactor system with (^{232}Th-^{233}U) oxide fuel. The physics design principle will be briefly described here.

PHYSICS DESIGN PRINCIPLES

If natural thoria rods, without any external seed, are placed in the ambience of large thermal neutron flux, a fairly high rate of fertile to fissile conversion occurs. Initial conversion rate is nearly three times that for uranium rods subject to the same neutron fluence. In a thermal reactor neutron spectrum, the asymptotic stable concentration of ^{233}U in thorium is about 1.5% and is distinctly higher than the plutonium formed from uranium. Apart from lower thermal capture cross section of ^{238}U, the thermal absorption cross section of plutonium isotopes is more than two times that of ^{233}U. Hence plutonium production rate is low and consumption rate is high. Plutonium content in uranium rods therefore does not rise much above 1%, even after a long residence time at high neutron flux. In reactors using natural uranium, the residence time is short and hence the plutonium content in discharged fuel is just about 0.3%. The even isotopes ^{240}Pu and ^{242}Pu of uranium burnup chain are non-fissile. They accumulate much more than the even isotopes ^{234}U and ^{236}U of thorium burnup chain. ^{233}U is a far superior fuel compared to plutonium for reuse in thermal reactors owing to its much larger η value. Plutonium is a better fuel for fast reactors for the same reason, but in fast energy range. Fast reactors need however much more fissile material inventory for a given reactor power. When one is contemplating large scale utilization of thorium, thermal reactor is a better option. As can be seen, there are certain advantages of irradiating thorium in comparison to uranium, if one desires a superior and larger residual fissile content in the discharged fuel.

In order to exploit the above physics advantage, we must explore the ways and means of increasing the thoria loading in a power reactor design. Reactors using natural uranium, after reaching equilibrium condition, have practically no excess reactivity. They cannot accommodate thoria rods without any external seed or without some penalty in the already limited discharge burnup of natural uranium. Reactors using enriched uranium have large excess reactivity. This reactivity is compensated normally by some control absorbers in the form of control rods, burnable poison rods containing Gd, ^{10}B etc. and/or soluble boron in moderator. This leads to wasteful neutron captures with no tangible returns. If these neutrons are used for fertile captures in thoria rods, one can use the excess fission neutrons far more effectively. Thoria rods, which behave like absorber rods to start with, turn into regular fuel rods after they accumulate adequate content of the fissile isotope ^{233}U. The geometrical disposition of these thoria rods has to be suitably devised.

A light water breeder reactor (LWBR) was operated successfully at Shipping Port, Pennsylvania, U.S.A. This reactor employed (^{232}Th-^{233}U) fuel. An initial inventory of 501 kg of ^{233}U was used and after five years of operation from 1977 to 1982 a net breeding ratio of 1.013 was reported [7]. It may be noted that the above LWBR started with the man-made fissile isotope ^{233}U. The reactor power was 90 MW(e). Tight lattice spacing was used to enhance the neutron flux in resonance energy range. Varying ^{233}U contents was used in the seed and blanket regions.

In light water reactors, which need higher enriched uranium, the thermal flux level is somewhat lower than in heavy water reactors of same power. The thermal flux level could be lower by a factor of five. When tight lattice spacing is used, epi-thermal flux is enhanced and one would obtain an intermediate neutron spectrum. If thoria rods without any seed material are to be placed in such a spectrum, there are several factors inhibiting the rapid fertile to fissile conversion in thoria rods.

- Higher thermal neutron capture cross section of ^{232}Th cannot be exploited.
- Intermediate spectrum would require higher seed enrichment. Thoria rods would have to compete with the seed fuel rods that are placed in close proximity due to tight lattice spacing.
- Due to poorer rate of neutron capture, the thoria rods are designed to reside for much longer period. In the WWER-Thorium reactor design, the thoria rods are allowed to reside for as long as nine years while the seed is changed every year [8].
- In intermediate spectrum, neutron capture by ^{233}Pa is enhanced, since it has significant resonance or epithermal capture cross section. In this case the direct formation of ^{234}U isotope is enhanced and a ^{233}U isotope is lost.
- Power mismatch between seedless thoria rods and enriched fuel is substantial and would pose problem in thermal hydraulic design.

In view of the above physics reasoning, it was felt that one must design a core in which there are some islands of high thermal neutron flux trapped in pure moderator regions with low thermal capture probability in the moderator itself. D_2O is the best moderator satisfying this requirement. Fig. 1 illustrates this physics phenomenon.

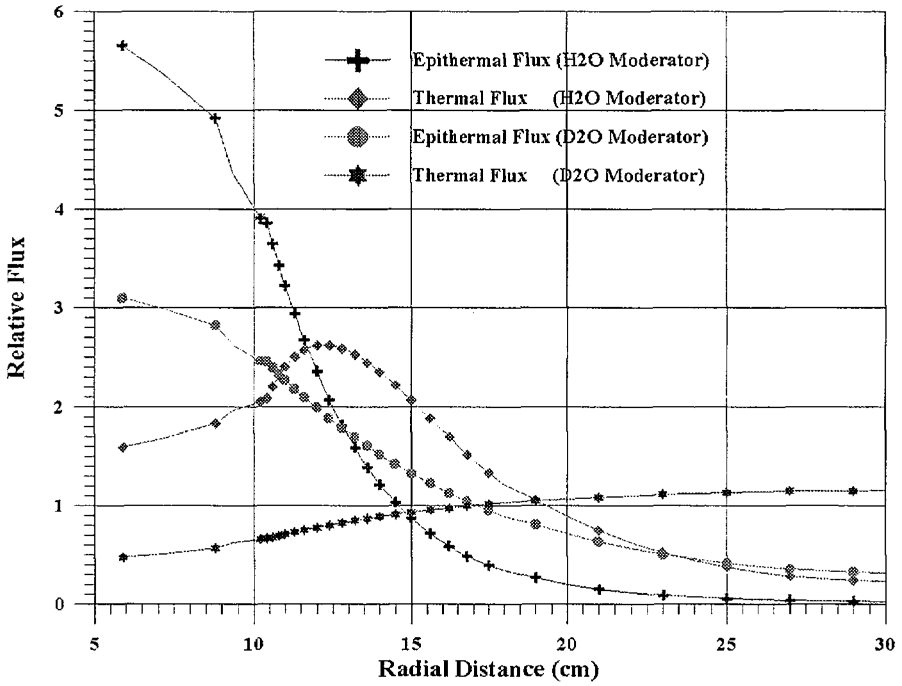

Figure 1. Relative flux distribution across the fuel assembly (H_2O moderator vs. D_2O moderator).

A theoretical study was made in which some seed fuel rods are surrounded by thick moderator regions of either light water or heavy water. The fluxes are normalized such that total absorption in the problem domain is unity. It is seen that in case of light water both epithermal and thermal neutron flux fall rapidly while in case of heavy water moderator the thermal neutron flux increases and remains flat for significant radial distance. It must be added that there was practically no loss of reactivity with increased moderator thickness in case of heavy water while in case of H_2O, the reactivity decreased rapidly. Thus with respect to critical system, the D_2O moderator case is more realistic. One would be able to find ample space for accommodating thoria rods.

D_2O moderated and boiling H_2O cooled reactors have been designed and operated in the world. These reactors are called by different names. In U.K., it was called Steam Generating Heavy Water Reactor (SGHWR) [9]. This type of reactor is ideally suited for irradiating fresh thoria rods in a seed and blanket type arrangement, where every blanket type thoria cluster can be surrounded by seed fuel clusters.

We have designed a new reactor with SGHWR like geometry. We consider a vertical pressure tube type reactor arranged in hexagonal type lattice structure. Fig. 2 gives the cross sectional view of the optimized core loading for an equilibrium core with a typical five batch refueling scheme. Fig. 3 gives the cross sectional view of a blanket type thoria ring cluster with 30 ThO_2 rods. Fig. 4 gives the cross sectional view of the seed fuel cluster with 54 enriched UO_2 fuel rods and 30 ThO_2 rods.

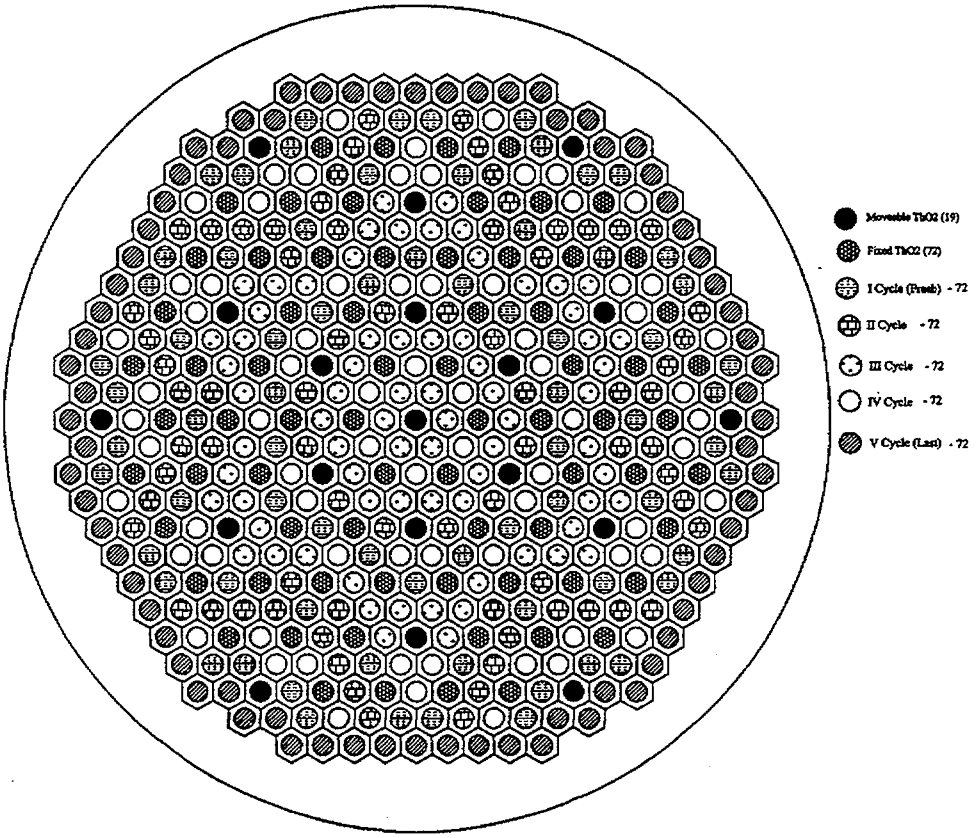

Figure 2. ATBR Core - 360 (eUO_2+ThO_2) + 91 ThO_2 Fuel Clusters 72 Assemblies/Batch - 5 Batches - Optimized Loading Pattern.

A new and unique feature of the core design is that the thoria rods require no external feed enrichment. The core consists of at least one batch size of such 30 rods thoria clusters. They are spread through out the reactor core except the one or two peripheral layers with twice the fuel assembly lattice spacing. They face the high thermal neutron flux similar to the one described in Fig. 1. By residing in the reactor core for one fuel cycle duration, they accumulate adequate ^{233}U. The irradiated thoria clusters are integrated with fresh enriched UO_2 seed fuel rods placed in two inner fuel rings. The integrated clusters undergo five more fuel cycles of operation following the shuffling scheme illustrated in Fig. 2. At the end of five cycles the thoria rods as well as enriched UO_2 rods attain a fairly high discharge burnup of

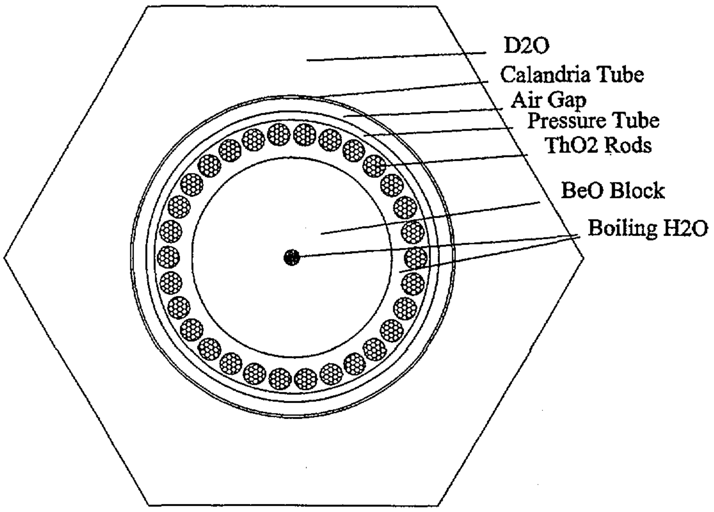

Figure 3. ATBR - 30 Rods ThO2 Fuel Cluster.

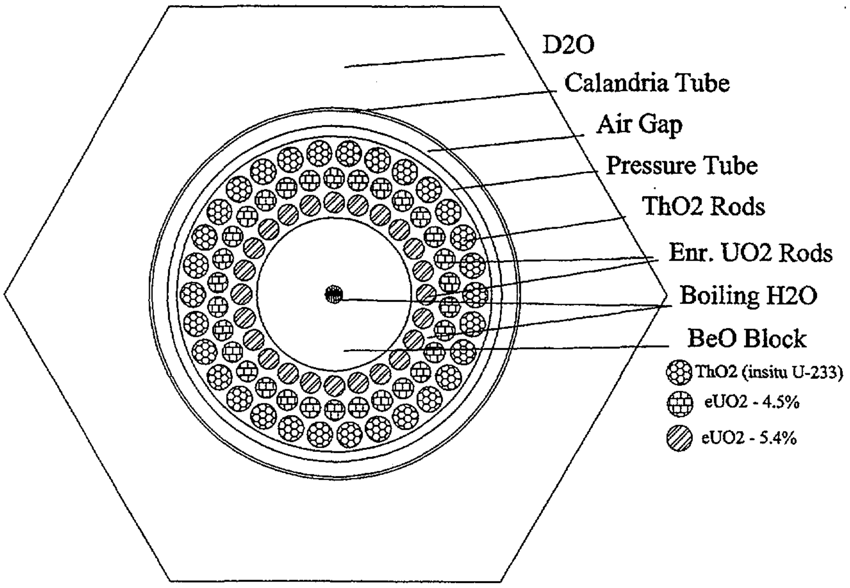

Figure 4. ATBR - 54 eUO2 + 30 ThO2 Rods Fuel Cluster.

32 GWD/T. The enrichment in UO_2 seed is about 5% ^{235}U . The fuel clusters consider some filler scattering material block like BeO in the centre. This arrangement was needed since the fuel cluster size was deliberately chosen to be large to achieve negative void coefficient. To minimize the power peaking within the fuel cluster, the central 37 fuel rods were removed and replaced by a scattering medium. More details of the core design are available in the references and are not reproduced here.

There are several interesting features of the new core design.

- At full power operation, there is practically no need for external reactivity control mechanisms since the K_{eff} variation is only 4 mk in 300 effective full power days. This can be nearly met by coolant inlet enthalpy variation.
- The power distribution is intrinsically maintained with comfortable thermal margins.
- The xenon override reactivity is about 20mk for full power operation. This can be provided by withdrawal of 19 moveable thoria clusters.
- The core can be deemed to be inherently safe since the most common transients involving reactivity excursions like rod ejection, loss of coolant, cold water addition etc are either absent or far less severe for this reactor.
- There is a sizeable production of ^{233}U which is intrinsically proliferation resistant due to formation of the isotope ^{232}U and high gamma emitting daughter products thereof. ^{232}U formation is however much lower owing to the neutron spectrum which is essentially a thermal one.
- Equilibrium loading of uranium and thorium is 50:50 by weight.
- There is no need for fuel reprocessing, if enriched UO_2 is available. Even in the closed fuel cycle options, the reprocessing load would be nearly halved, since 50% of the core can continue to use fresh ThO_2 in its natural form.
- Other types of seed zones employing either ^{233}U in natural uranium/thorium or plutonium in natural uranium/thorium are possible. Of these, the option of ^{233}U in thorium has the potential of being developed into a thermal breeder.

SUMMARY AND CONCLUSIONS

For utilization of thorium a new reactor concept with SGHWR like geometry is proposed. This reactor has two operational phases. In phase-I, it is a pre-breeder, i.e., an efficient ^{235}U to ^{233}U converter. Phase-II will be a breeder or at least a self-sustaining reactor system with (^{232}Th-^{233}U) oxide fuel. In our opinion, burning of thorium in the ambience of enriched UO_2 fuel is far superior to waiting for accumulation of plutonium from uranium reactors. Induction of thorium helps to cut down the uranium requirements. The new reactor concept has an overall better economic, operational and safety characteristics in comparison to any of the power reactor designs that are currently operational, albeit theoretically. There is no need for fuel reprocessing, if enriched UO_2 is available. Even in the closed fuel cycle options, the reprocessing load would be nearly halved, since 50% of the core can continue to use fresh ThO_2 in its natural form. This is permanent gain for future reactors. These reactors can use the same engineering design [6].

The present work is a theoretical study with the cross section data and calculation tools available with the author. Some uncertainties in the calculated results are admittedly present. Notwithstanding the above, it is claimed that the proposed reactor design has indefatigable design features which are convincingly superior to those of the power reactor designs prevalent today. It is mandatory to perform some physics experiments to refine the design parameters. The emphasis is laid more on the design philosophy rather than on the design parameters themselves.

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