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THORIUM UTILISATION IN THERMAL REACTORS

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Abstract

It is now more or less accepted that the best way to use thorium is in thermal reactors. This is due to the fact that U233 is a good material in the thermal spectrum. Studies of different thorium cycles in various reactor concepts had been carried out in the early days of nuclear power. After three decades of neglect, the world is once again looking at thorium with some interest. We in India have been studying thorium cycles in most of the existing thermal reactor concepts, with greater emphasis on heavy water reactors. In this paper, we report some of the work done in India on different thorium cycles in the Indian pressurized heavy water reactor (PHWR), and also give a description of the design of the advanced heavy water reactor(AHWR).

1. Introduction

In the initial days of nuclear power, conventional wisdom decreed that reactors based on the fissioning of U235 alone will not be able to provide all the energy requirements of the world, and a large body of work on thorium was carried out in those days. With time, however, power growth slowed down in the developed world, the light water reactor became very successful and captured 85% of the nuclear power market, and the nuclear community put thorium on the back burner.

India, which has vast deposits of thorium and limited uranium resources, has drawn up its nuclear power program to consist of three phases, of which the third and final phase envisages the use of thorium on a large scale. In preparation for the decisions to be taken for the third stage, we studied the use of thorium in all of the existing reactor concepts.

2. Energy Potential of Thorium

Before looking at the different possible options, we take a look at the energy potential of thorium in thermal reactors, which is very much greater than that of uranium. This fact is often forgotten these days, mainly due to the glut of low cost uranium in the

Western world. Table 1 emphasizes this point by showing the mount of energy that can be extracted from 1000 tone of natural uranium using three different systems.

3. Existing Concepts

Thorium cycles were analyzed in the following systems

(a). Light water breeder reactor (LWBR).
(b). The high temperature gas cooled reactor (HTGR).
(c). The molten salt breeder reactor (MSBR).
(d). The aqueous suspension heavy water reactor.
(e). The open lattice heavy water reactor.
(f). The pressurized heavy water reactor (PHWR).
(g). The advanced heavy water reactor (AHWR).
(h). The source driven reactor.

The best resource utilization of thorium was, not unexpectedly, in the MSBR. The next best system turned out to be the heavy water reactor. Since the work horse of the Indian nuclear power program is the PHWR, we have examined various ways of using thorium in the PHWR.

The PHWR is basically a system that was optimized for uranium. As such, the use of thorium in this system is basically a form of retrofitting. It is interesting to see what it would be like if the reactor itself were to be optimized for thorium. This has led to the design of the Advanced Heavy Water Reactor (AHWR).

This paper then consists of two parts. In the first, we describe various ways of using thorium in the PHWR. In the second, we provide some insight into the design of the AHWR.

4. Description of the PHWR

The Indian PHWR is a tube type reactor using heavy water as both coolant and moderator. The coolant is physically separated from the moderator by being contained inside the pressure tube where it is maintained at high temperature and pressure. The moderator heavy water is at relatively low temperature and is unpressurized.

The reactor core consists of 306 pressure tubes arranged along a square lattice of 22.86 cms pitch. The fuel pins and the coolant are contained within these pressure tubes. The fuel is a cluster of 19 rods and is divided into bundles of 49.5 cms length. Every channel contains 10 such bundles in the active portion of the core. Refuelling is done by simply pushing out eight bundles from a channel on one end, while eight fresh bundles are inserted from the other end.

5. Thorium cycles in PHWR

In broad terms, three kinds of thorium fuel cycles are possible in the PHWR. These can be named as the self-sustaining equilibrium thorium cycle (SSET), the high burnup, high conversion ratio cycle, and the once through thorium cycle (OTT).

5.1. The self-sustaining equilibrium cycle

In this cycle, the fuel in the equilibrium stage is thorium-U233. The initial enrichment of U233 in the thorium is so adjusted that the quantity of U233 recovered from the spent fuel will be exactly sufficient to provide the enrichment for the reload fuel. This cycle can give a discharge burnup of 11000 - 12000 MWD/T. This burnup is too low for a cycle that calls for reprocessing and possibly remote fabrication of fuel. The discharge burnup can be increased by adding a small amount of makeup fissile material to the fresh fuel.

Figure 1 shows the energy production in an SSET cycle with U235 makeup. Since there is no net destruction of U233, it can be assumed that all the energy is coming from the destroyed U235. We see that as the discharge burnup increases, the energy extracted reduces. Also shown in the same figure is a similar curve for low enriched uranium, and we can see the immense advantage one gets by going for the thorium self-sustaining cycle.

5.2. The high conversion ratio high burnup cycle

The major problems of the SSET are the need for reprocessing, and for U233 fabrication. The high burnup thorium cycle avoids these. This cycle would be of particular interest to those countries which subscribe to the concept of direct disposal of spent fuel, because high burnup enables one to shrink the spent fuel inventory. High burnup is of course, equally possible with leu too, but the advantage of thorium over leu lies in the fact that for the same high discharge burnup, the initial fissile content required is lower with thorium fuel. Figure 2 shows discharge burnup as a function of initial U235 content for leu fuel and for thorium-U235 fuel. One sees that for low enrichments, leu gives higher discharge burnup, but for very high discharge burnups, the enrichment required for the thorium fuel is lower than that required by the leu. For a discharge burnup of around 66000 MWD/T, the leu requires an enrichment of 4.5%, whereas the thorium needs only 3.5%. Add to this the fact that thermal absorption in thorium is about three times that in U238, we can see that the initial reactivity in the thorium core will be much below that of the leu core for the same discharge burnup. This leads to lower reactivity swings, which is a definite operational advantage.

5.3. Once through thorium (OTT) cycle

The two cycles described above call for an overall changeover to thorium cycle from the uranium cycle. Utilities are often reluctant to leave the familiar ground of uranium cycle. Originally proposed by Milgram (ref. 1), the OTT scheme suggests a way of introducing thorium that causes the least disruption in the normal fuelling of the reactor.

The scheme consists of leu or MOX fuel in most of the PHWR with a few channels being loaded with unenriched thorium. Since the channels are segregated, it is possible to vary the discharge burnup of thorium fuel and uranium fuel independently. The central point of the OTT is that the thorium fuel should be irradiated to very high burnups. At low burnups, the thorium is a load on the uranium, and so the presence of thorium causes a decrease in the energy obtained from uranium. With increasing thorium burnup, the U233 which builds up starts producing power, and the sum total of energy extracted from uranium and thorium can become larger than what is achievable with uranium alone. At still higher burnups, the accumulated fission product poisons cause the energy extracted to come down once again. This variation can be clearly seen in figure 3.

6. Beneficial Uses of Thorium in Fuel Management

Judicious placement of thorium in various locations in the reactor core can often help in improving the core power distribution. This effect is more pronounced in the PHWR or CANDU kind of reactors where the fuel is in the form of short bundles.

6.1. Initial power flattening in the PHWR natural uranium core

Power flattening in the equilibrium core of the PHWR is achieved by having higher burnup fuel in the central region. In the fresh core, this effect could be obtained by using thorium bundles. But in the process it was also important to ensure that the negative reactivity worth of the primary and secondary shut down systems do not decrease. The loading shown in figure 4 was worked out in such a manner that all these three constraints are met.

6.2. Reactivity suppression in the initial PHWR leu core

Slightly enriched uranium for the CANDU type reactors is generally being considered these days. One could either start a new core fully loaded with leu bundles, or one could have a gradual transition from the natural uranium PHWR to the leu core. In the second case, the transition has to be handled without undue derating in the transitional phase. In the first case, the initial core will be very highly reactive, and this reactivity has to be contained. One way of course, is to use boron in the moderator. But the initial reactivity of the leu core could be as high as 250 mk, and to absorb all those neutrons in boron is hardly an elegant solution and is, in any case, a negation of the very basic idea behind heavy water reactors, viz., neutron economy.

Our studies have found that this reactivity can be suppressed by thorium bundles. Figure 5 gives the loading that satisfies these requirements. In the Indian PHWR for which this problem was analyzed, the power constraints were: full power 655 MW(th), maximum bundle power 420 kW, maximum channel power 2.75 MW, and maximum coolant outlet temperature 297 C. The figure shows that all these constraints are met. The numbers given in the space for each channel are the axial positions of the thorium bundles in that channel. For convenience of writing, bundle position:10 has been represented by 0. Most of the channels have more than one thorium bundle, in some cases there are three or even four.

Apart from these two, we have also studied a detailed fuel management scheme for the transition of a natural uranium PHWR to a MOX core, the transition being facilitated by adding a few thorium channels.

7. The Advanced Heavy Water Reactor (AHWR)

All that has been described above is basically a retrofit into a reactor system that was evolved and optimized for the uranium cycle. But thorium deserves to have a reactor which is optimized for the special nuclear characteristics of thorium even from the design stage. The AHWR is the result of such an exercise.

The design objectives of the AHWR are briefly: (i) about 75% of the power produced by the AHWR should be contributed by thorium; (ii) the system should have negative void coefficient of reactivity; (iii) discharge burnup of the fuel should be about 20,000 MWD/T; (iv) plutonium consumption and initial plutonium inventory should be as low as possible; (v) the system should be self-sustaining in U233; and (vi) the total thermal power of the reactor should be about 750 MW(th).

Point no. (v) above decides that the starting point will be the SSET cycle described in art. 5.1. In order to extend the burnup of the SSET, we use plutonium as makeup fissile. Pu239 has a rather high capture-to-fission ratio in the soft spectrum of the PHWR. To put plutonium in a favourable spectrum, the lattice is made relatively tight and undermoderated as compared to the PHWR.

Thorium oxide has got very good fuel performance characteristics, and is capable of going on to very high burnups. Since this has to be matched by reactivity considerations, the initial plutonium enrichment could be very high. This would have the undesirable consequence of too high a fraction of the power coming from plutonium. The problem has been solved by concentrating the plutonium in a small number of pins. In the AHWR cluster, which is a 52 rod cluster, only eight pins contain plutonium, the other 44 being thorium-U233. These eight pins are replaced more frequently than the remaining 44, thus making a lower plutonium enrichment acceptable, and the fractional power production from plutonium correspondingly lower.

The thermal absorption of thorium is three times that of U238. Due to this, the deleterious effects of parasitic absorption are less in thorium systems, and one can consider the use of light water coolant. This opens the way to direct cycle and in-core boiling. The reactor then has to be vertical, and then it becomes possible to design for 100% heat removal by natural circulation and passive safety. The possibility of positive void coefficient of reactivity has been countered by the lattice being undermoderated.

A description of the AHWR at the current stage of evolution is given in table 2.

8. Remarks

Thorium cycles have a degree of flexibility, and particularly in the context of heavy water reactors which use short bundles, this can be used to great advantage in transitional fuelling. On the other hand, they hold out promise for good fuel utlisation (SSET), high burnup and other objectives like plutonium dispositioning. In this paper, we have not said anything about this last, but some work is in progress in this area and will be reported in a future paper.

9. References

1. "Once through thorium cycles in CANDU reactors", M.S. Milgram, AECL-7516.

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Table 1. Electricity Generation from 1000 Tons of Natural Uranium

Table 1
Electricity generation from 1000 tons of natural uranium

	Installed capacity MW(e)	years of operation that can be sustained
LWR on uranium cycle	185	30
PHWR on uranium cycle	262	30
PHWR on thorium self-sustaining cycle	440	for all time to come

Table 2. Description of AHWR at the Present Stage of Evolution

Reactor power MW (th)	750
Reactor power MW(e)	220
Fuel description	
Number of pins	52
Number of Pu bearing pins	8
Number of thoriumU^{233} pins	44
Number of water tubes for ECCS injection	8
Plutonium content in MOX (%)	4.5
U^{233} content in thorium	self sustaining
Coolant water density (varies in the range)	0.50-0.55
Total number of channels	408
Number of seeded clusters with all "thorium-U^{233}" pins	304
Number of fuelling zones	3
Number of reconstitutions	2
Thorium pins discharge burnup MWD/Te	20,000 approx.
MOX pins discharge burnup MWD/Te	20,000 approx.
Lattice pitch (cms)	29.4
Active fuel length (cms)	350
Moderator and reflector	D2O
Scatterer balls in the moderator	pyrocarbon
Calandria radius (cms)	380
No. of adjustor rods	4
Worth of adjustor rods (mk)	3.12
No. of SDS-1 rods	24
Worth of SDS-1 (mk)	37.2
Performance data in equilibrium core	
Radial form factor	1.11
Hot spot factor in the seeded cluster	2.33
Hot spot factor in the thorium-U^{233} cluster	1.37
Maximum channel power (MW)	2.3
Maximum-to-minimum channel power factor	1.37
Fraction of power from thorium (%)	75.0

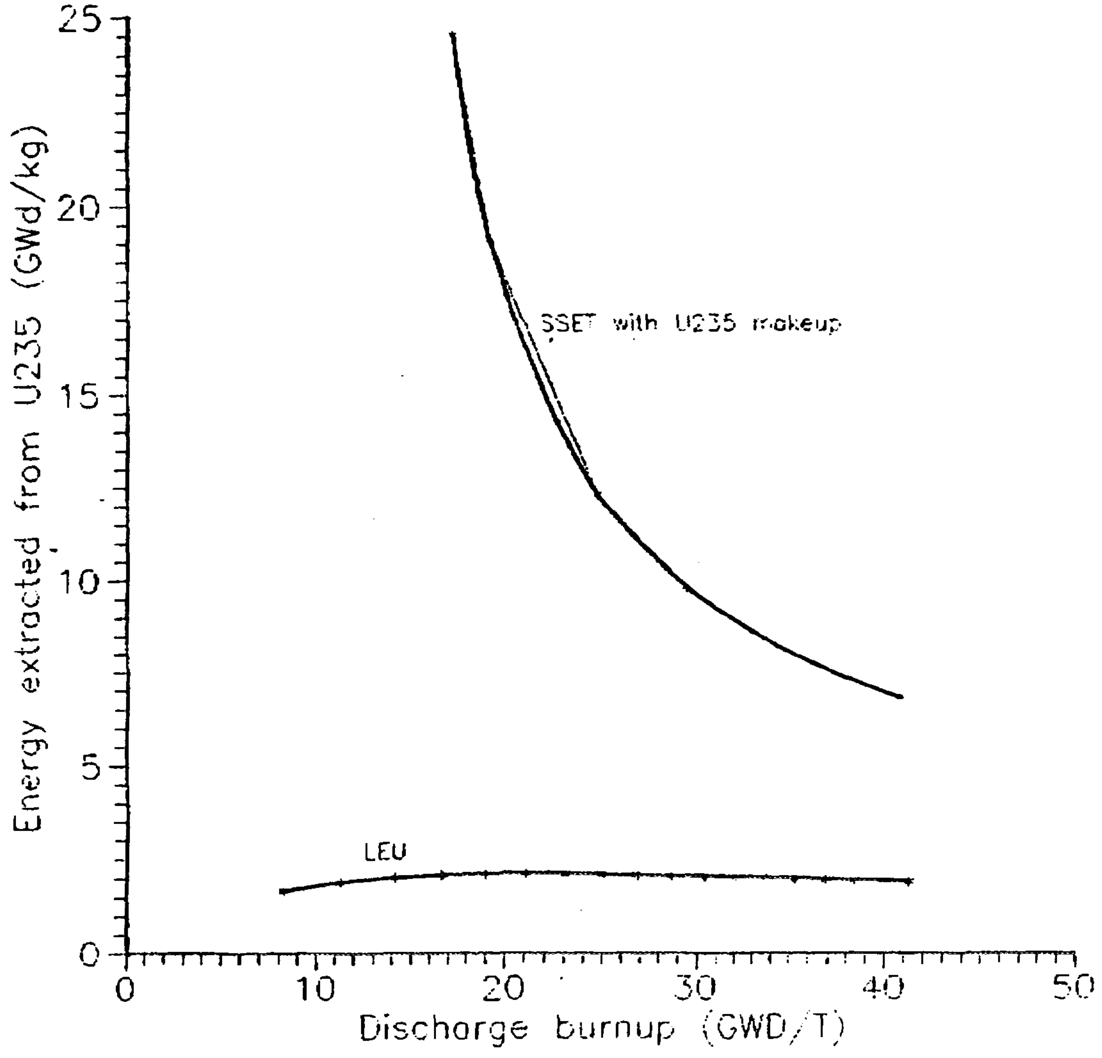


Fig. 1. Comparision of SSET and LEU Cycles

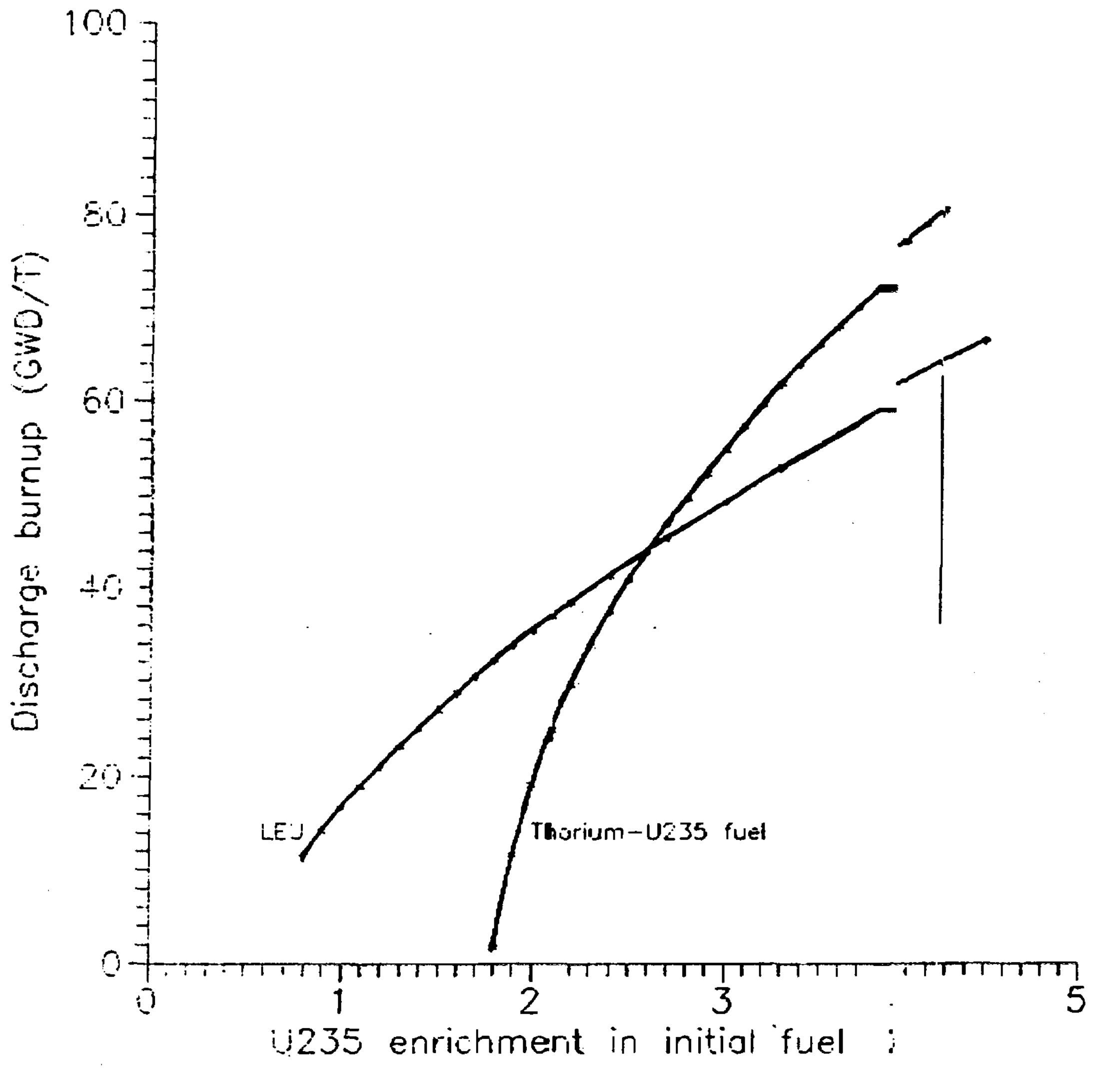


Fig. 2. Comparison of Thorium and Uranium Cycles for High Burnup

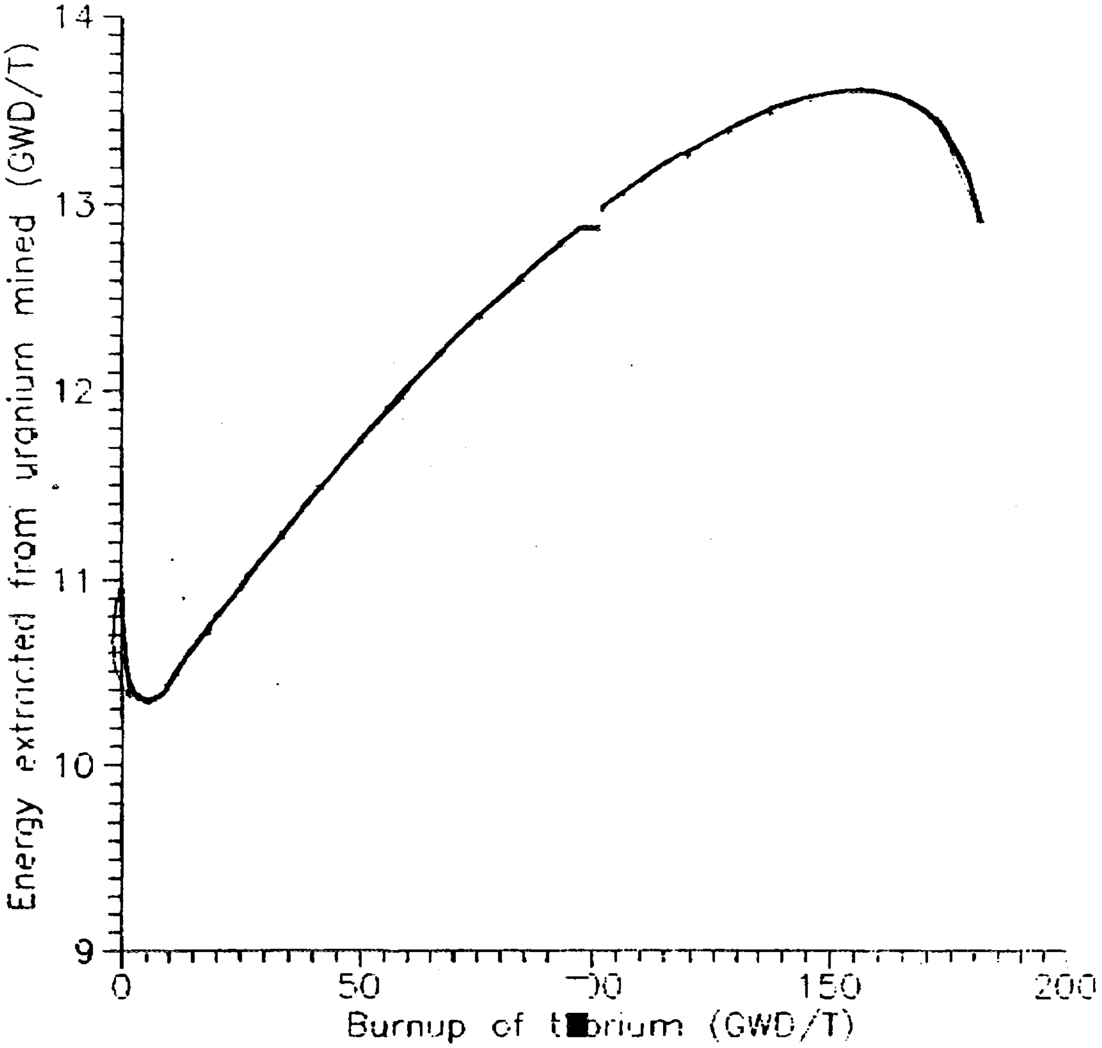
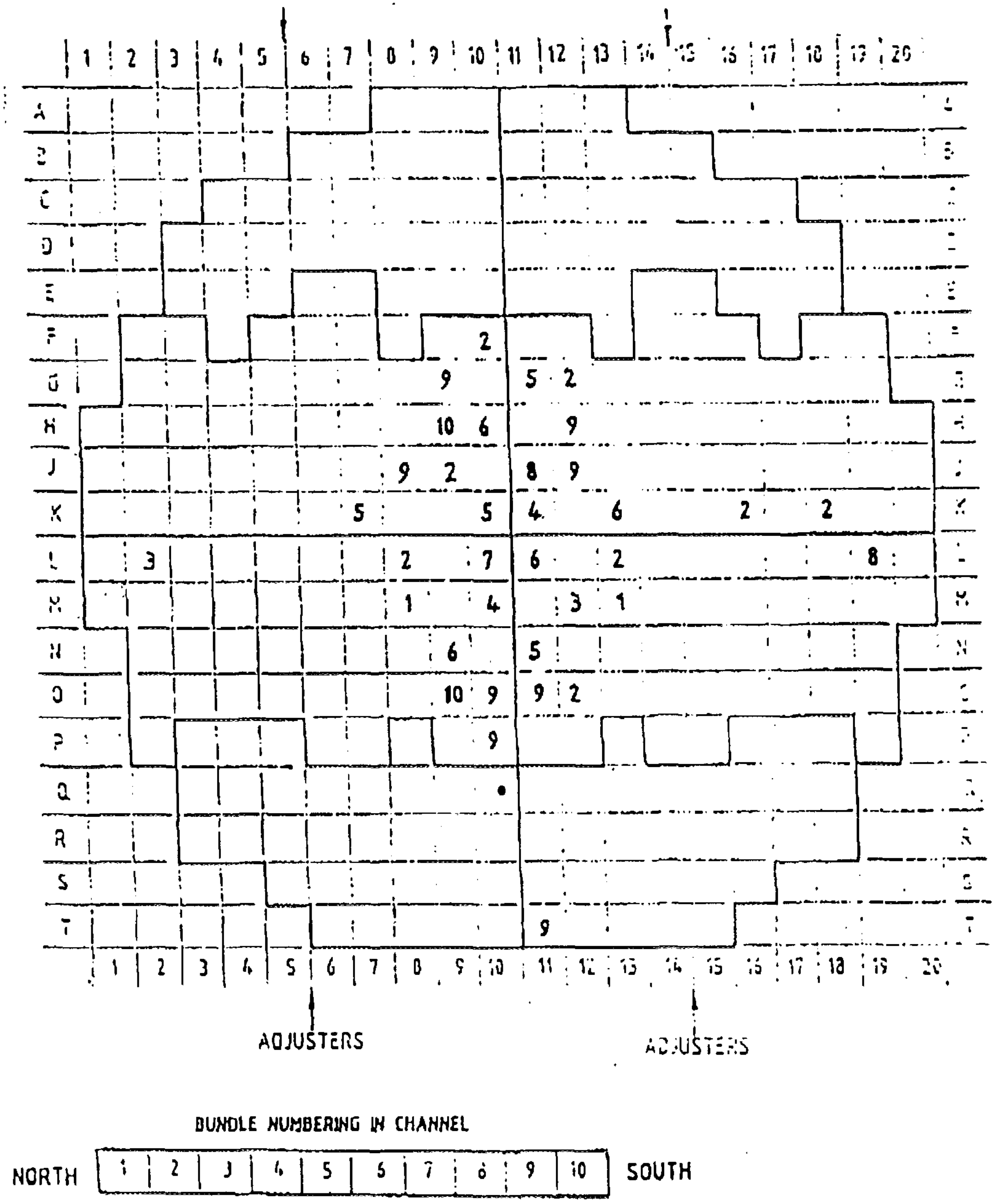
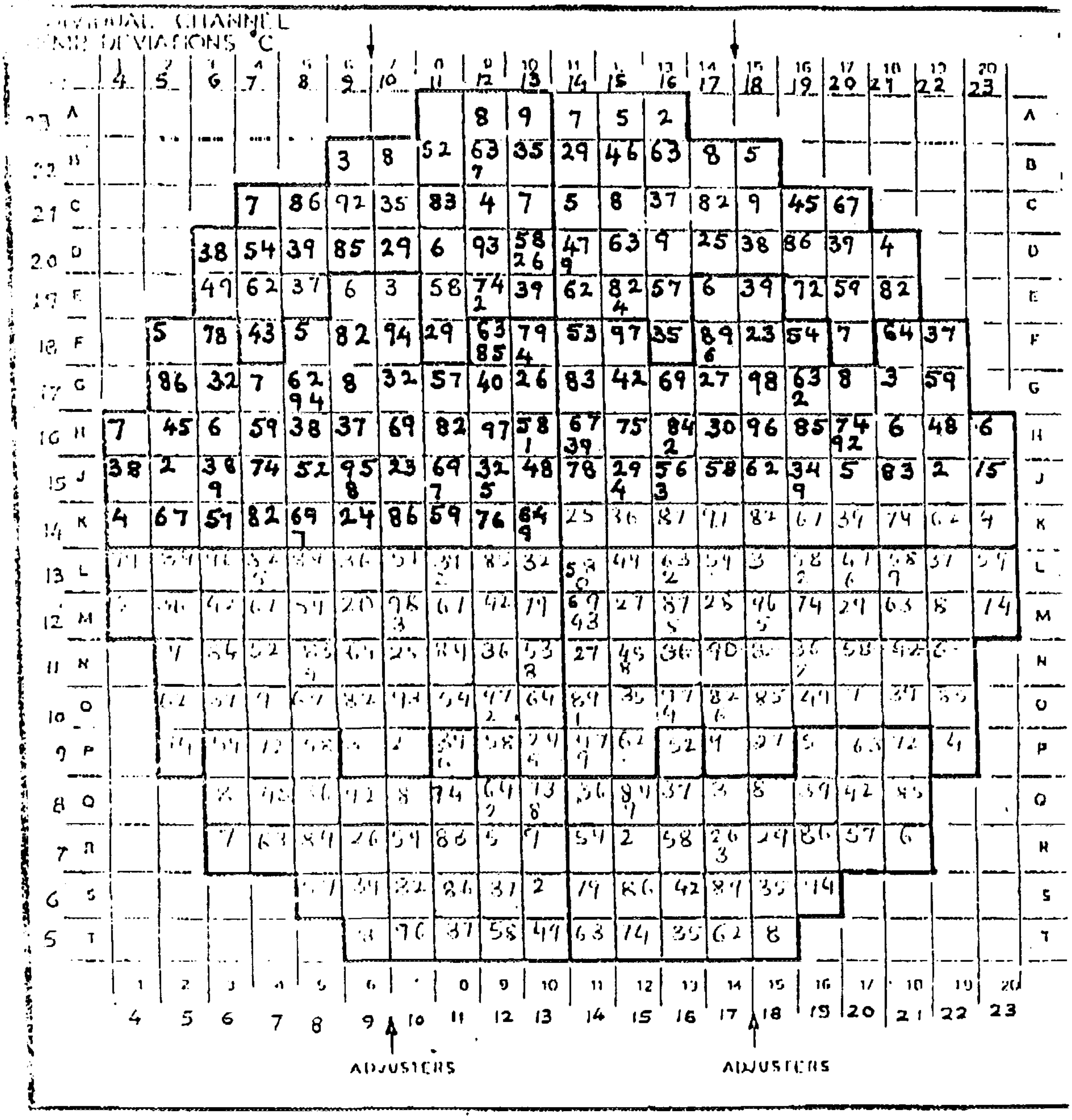


Fig. 3. Energy Obtained in the OTT Cycle



35 THRIUM BUNDLES. AXIAL POSITION IN THE CHANNEL INDICATED BY NUMBER. WRITTEN IN THE CHANNEL. REMAINING 3025 BUNDLES ARE NATURAL URANIUM.

Fig. 4 Thorium Loading - 2 Obtained by Optimisation



	VALUES IN THIS LOADING	HIGHEST VALUES PERMITTED
MAXIMUM CHANNEL POWER	2.71 Mw	2. 75 Mw
MAXIMUM BUNDLE POWER	389 Kw	420 Kw
MAXIMUM COOLANT OUTLET TEMP.	296. 6 °C	297 °C

K-eff = 1.04145

Fig. 5. LEU Core with Thorium Bundles Used for Reactivity Suppression