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# Advanced Thorium Cycles in LWRs and HWRs

INFCE/WG.8/ISRAEL/DOC 8

# ADVANCES THORIUM CYCLES IN LWRs AND HWRs

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# Seed Blanket Close Packed Heavy Water Breeder

by A. Radkowsky

The Seed Blanket Close Packed Heavy Water Breeder provides the possibility of obtaining with aqueous technology the ranges of breeding up to now thought to be attainable only with the Liquid Metal or Gas Cooled Fast Breeders. At first sight the use of heavy water for breeding would not seem to be very promising since for CANDU to get even a self-sufficient thorium cycle it is necessary to go to extremely expensive measures, such as decreasing the calandria tube thickness and increasing the heavy water purity. However, It will be seen that with the seed blanket concept we are using an essentially different approach. We are working with practically a fast spectrum, rather than the extremely thermal spectrum of CANDU reactors.

The attached figure shows the basic principle. It would seem from the right hand side of the figure that the way to improve the Initial Conversion Ratio, ICR, is to move to greater and greater moderator-fuel atom ratios. Most of the work on heavy water breeding has been done in the range from B to C. It was found that as we decreased the amount of moderation in moving from C to B the ICR was reduced, and it was assumed that this trend w continue until D. Actually we found that the ICR reaches a minimum and then starts a steady rise as the thorium rods are brought closer together. The explanation is found in the fact that when the moderation is extremely reduced we are approaching the fast reactor regime. In fact for the uranium-plutonium cycle the rise is even greater in Initial Conversion Ratio. However, in the interests of nonproliferation it is desirable to work with the thorium cycle w just enough uranium-238 to produce denatured fuels.

In the design we borrow certain ideas from the Light Water Breeder, LWBR, including Geometry Control and the unitized arrangement. Geometry Control results in optimum conservation of neutrons. The seed is zoned axially so that movement of the seed regulates the leakage of neutrons from the seed to the blanket. The greater the leakage the lower the core reactivity, and vice versa. This means that all excess neutrons are absorbed by the blanket, composed primarily of fertile material. This is in contrast to conventional reactors in which neutrons are absorbed wastefully by control rods and equivalent absorbers. In the unitized arrangement the core is composed of identical modules, each consisting of a seed blanket assembly. We can now obtain a core for greater power output simply by adding to the number of modules, rather than having to do a core redesign, as is the case in conventional PWRs.

The LWBR has been criticised for its very high specific loading of fissile fuel. The primary reason for this was to keep the protactinium losses low and also the necessity of obtaining breeding in the seed, as well as in the blanket, in order to breed at all. Thus use of fertile material in the seed, a location of high k-infinity,immediately forc the fissile loading to a high value. In this heavy water breeder the intrinsic breeding is high enough so that fertile material can be almost or entirely eliminated from the seed. This reduces the specific fuel loading considerably, bringing it lower in value than the LMFBR. With the denatured fuel loadings the LWBR is unable to breed, since the U-238 results in the formation of Plutonium-239, which has too low a value of eta to permit breedin The breeding of LWBR is marginal at best with an over-all gain in fissile fuel of only abou 1% per cycle. Thus any perturbations which would lower the breeding are inadmissible. In the heavy water case we have seen that plutonium has a very good eta, so that the use of denatured fuels will not hurt the breeding. Thus we can employ and breed denatured fuels.

In the design of other fast breeders, such as the LMFBR, there is considerable concern over the positive void coefficient, that is the reactivity rises appreciably if the sodium is voided, as could happen in a LOCA which would cause the sodium to boil. According t our calculations this would not happen in the seed blanket heavy water reactor because the leakage from the highly multiplying seed to the subcritical blanket would be increased if the water were voided. Thus there would be anet decrease in the core reactivity.

This heavy water reactor could conceivably be used as a replacement core for LWRs. The plant modifications would be the same order of magnitude as for Spectral Shift Operation, except that no plant would be needed in this case to upgrade the heavy water, since we would not, of course, vary the heavy water content during the course of operation. Of course performance would be far better than for Spectral Shift. As compared with CANDU the performance of our Seed Blanket would be considerably better in breeding and the investment in heavy water considerably less. Thus this type of aqueous breeder seems to offer the best prospects for the future, when it becomes economic to reprocess denatured fuels.

**United States Patent** [19]
**Radkowsky et al.**

[11] **3,859,165**
[45] **Jan. 7, 1975**

# [54] EPITHERMAL TO INTERMEDIATE SPECTRUM PRESSURIZED HEAVY WATER BREEDER REACTOR

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[73] Assignee: **The United States of America as represented by the United States Atomic Energy Commission,** Washington, D.C.

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[21] Appl. No.: **297,545**

**Related U.S. Application Data**

[63] Continuation-in-part of Ser. No. 59,171, July 29, 1970, abandoned.

[52] **U.S. Cl.** .................................. **176/18,** 176/40
[51] **Int. Cl.** ........................................ **G21c 1/00**
[58] **Field of Search** ............ 176/17, 18, 205 SC, 40

[56] **References Cited**

UNITED STATES PATENTS

| | | | |
|---|---|---|---|
| 2,992,174 | 7/1961 | Edlund et al. | 176/18 |
| 3,143,478 | 8/1964 | Chernick et al | 176/18 |
| 3,183,376 | 5/1965 | Balent et al | 176/18 |
| 3,244,068 | 4/1966 | Schluderberg et al. | 176/18 |
| 3,252,867 | 5/1966 | Conley | 176/18 |
| 3,351,532 | 11/1967 | Rabb, Jr. et al | 176/17 |
| 3,379,615 | 4/1968 | Halliday | 176/18 |

OTHER PUBLICATIONS

"Hearings Before the Joint Committee on Atomic Energy, Congress of the United States," First Session on Naval Nuclear Propulsion Program, Apr. 23, 1969, pp. 199, 200, 202, 205, 206, 207, 210, 211, 222, 223.

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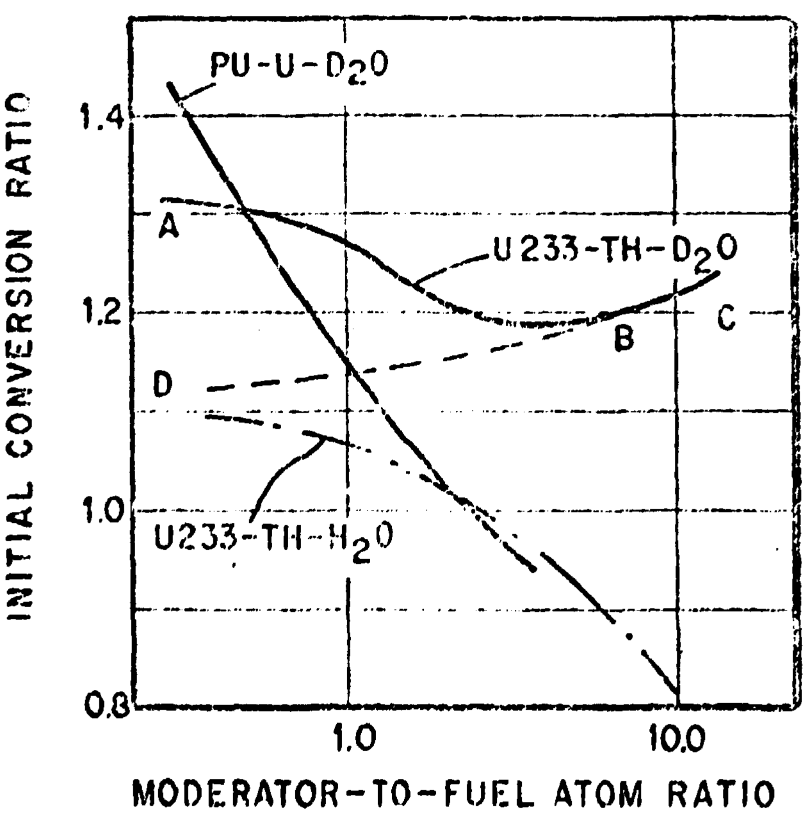
*Attorney, Agent, or Firm*—Kenneth L. Cage; John A. Horan

[57] **ABSTRACT**

A pressurized heavy water moderated nuclear reactor having an epithermal to intermediate neutron spectrum is provided which is characterized by an improved breeding ratio in comparison with previously existing pressurized heavy water moderated reactors. The neutron spectrum having an energy distribution between those of fast and thermal reactors results from the restriction of the moderator-to-fuel atom ratio to range from 0.35 to 4.0. Three pressurized heavy water reactor designs using the inventive moderator-to-fuel atom ratio range are described: two with a uniform lattice configuration and one with a seed-blanket arrangement.

**2 Claims, 10 Drawing Figures**



# Light Water Seed Blanket Thorium Burner

by A. Radkovsky

This concept is aimed at solving the problem of obtaining a large amount of energy from thorium, subject to three constraints:

Low initial uranium investment

No fabrication of U-233 fuel elements

Compliance with nonproliferation objectives.

The main reason for the second constraint is economic, it is expected to be extremely costly to fabricate U-233 fuel elements because of the high gamma radiation necessitating that all work be done behind heavy shielding by remote control.

In this burner concept we use many of the features developed in the Light Water Breeder Program, such as Geometry Control and unitized arrangement, but we retreat from the objective of breeding in favor of generating about 75% of the energy from thorium. We make use also of a feature of the first application of the Seed Blanket core at Shippingport, Pa, of burning the bred fuel in place in the blanket., except that now the bred fuel is U-233 instead of plutonium.

Geometry Control results in optimum conservation of neutrons. The seed is zoned axially so that movement of the seed regulates the leakage of neutrons from the seed to the blanket. The greater the leakage, the lower is the core reactivity, and vice versa. This means that all excess neutrons are absorbed by the blanket, composed primarily of fertile material. This is in contrast to conventional reactors in which neutrons are absorbed wastefully by control rods and equivalent absorbers. In the unitized arrangement the is composed of identical modules, each consisting of a seed blanket assembly. If now we desire a core having greater power output, we simply add to the number of modules, rather than having to do a core redesign as is the case for conventional PWRs.

In the LWBR the seed contains fertile material, thorium, which makes the fissile loading very high. This is not necessary in the burner concept since we are no longer straining for every neutron in to order to breed. However, we do not have to use highly enriched fuel in the seed, as was the case for the original Shippingport Application.

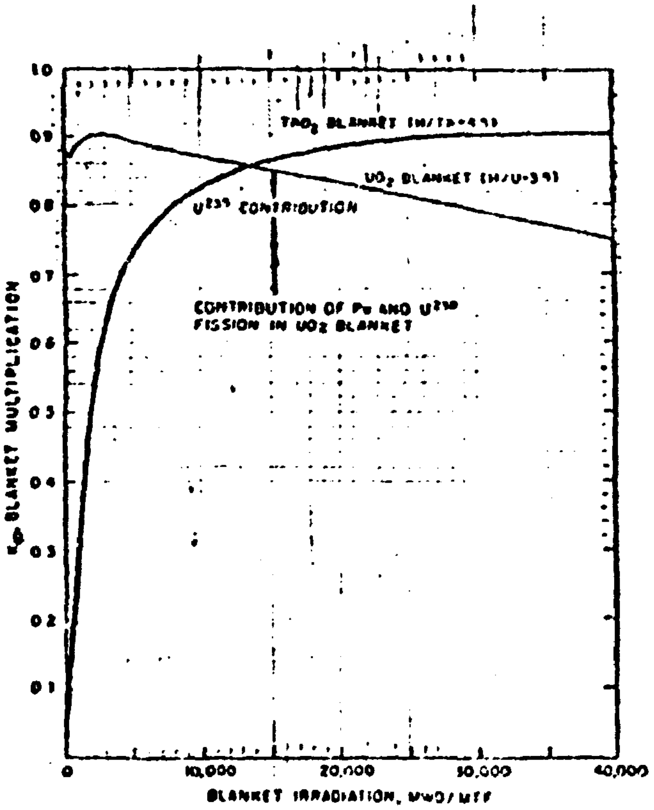
It turns out that we can use a denatured fuel, 20% U-235 in U-238, and actually reduce the fissile loading. This is because we get some plutonium burned with 20% enrichment, yet the amount of U-238 is not sufficient to greatly increase the critical mass.

In the LWBR the blanket rods were very closely spaced to reduce the neutron absorption by water and also to reduce the power density in the blanket so that the depletion of the bred U-233 would be minimized. In the burner concept we use relatively high water to fuel ratios in the blanket in order to maximize the multiplication factor of the blanket and increase its power sharing.

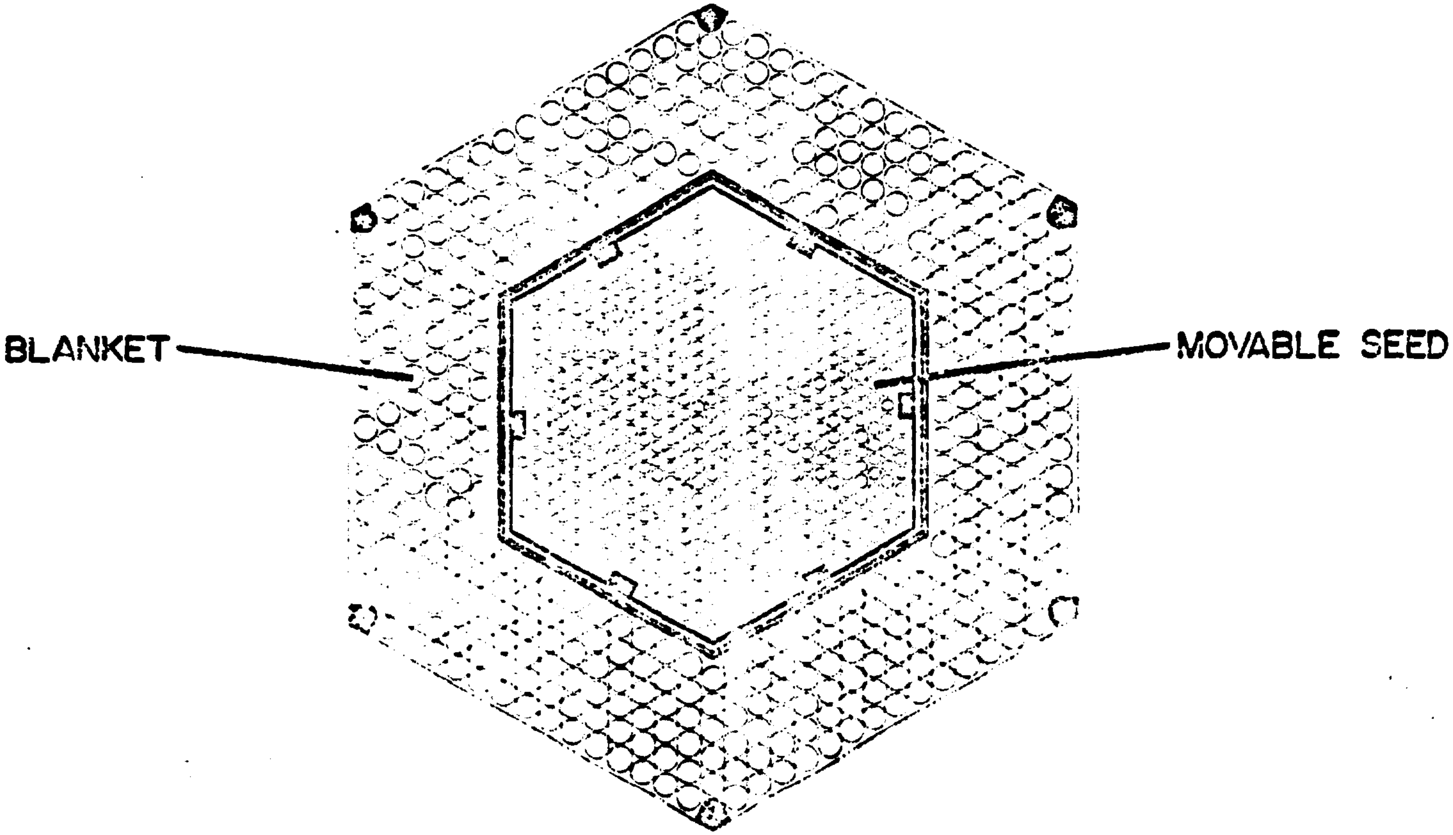
The figure shows the comparative behavior of the multiplication factors of a natural uranium and a natural thorium blanket. The natural uranium blanket starts with a high value, increases slightly in a relatively brief time, and then gradually decreases. The natural thorium blanket starts with virtually zero but eventually builds up to a higher value than that of the natural uranium maximum and maintains this value for a very long burnup. This means that a natural uranium blanket will generate considerable power at the start of core life while the natural thorium will generate almost nothing. On the other hand the thorium blanket will deliver more energy over the long run. A special design is utilized to combine the advantages of both blanket types. It is expected that the blanket irradiation will go to about 70,000 MWD/T, during which time it will deliver about 75% of the total core energy.

The advantage of the seed blanket concept in minimizing fissile fuel content is clear, since the seed acts a strong source or driver for the subcritical blanket. If the seed fuel were to be mixed uniformly with the blanket it would be necessary to get the fissile fuel absorption considerably greater than that of the thorium and other fertile material in order to have a sufficient value of k-eff. But then the conversion ratio would be low since the ratio of fertile material to fissile fuel absorption would be low. Further by having the seed as a separate region, we can periodically replenish the seed and leave the blanket in place. This idea of adding fissile fuel only as needed is somewhat reminiscent of a circulating fuel reactor. Actually we would plan to refuel the seed at a normal refueling interval of about once a year. The amount of seed fuel would decrease as the thorium blanket builds up in value of multiplication factor to a maximum which is held for a long time, that is we could decrease the amount of seed fuel necessary each year. The blanket would be left in the core until the irradiation limit is reached. It is not contemplated that the blanket will be reprocessed. However, if such reprocessing is considered necessary from a resource standpoint, the blanket will be the source of a denaturedfuel.

This core concept could actually provide a replacementcore for PWRs. It would be necessary only to change the pressure vessel head. There may have to be some adjustments in the main coolant pumps because of higher pressure drop in the seed. This type of core could provide the neartime solution to the energy problem, since it could save a great deal of uranium and yet be manufactured with no more expense than a conventional PWR and with much less uranium required. Since the core is 'once through', proliferation problems are avoided



. Comparison of $k_\infty$ Behavior With Irradiation for $UO_2$ and $ThO_2$ Blankets



~~Figure [illegible]~~. Typical LWBR Fuel Module Cross Section

*Fig* 3

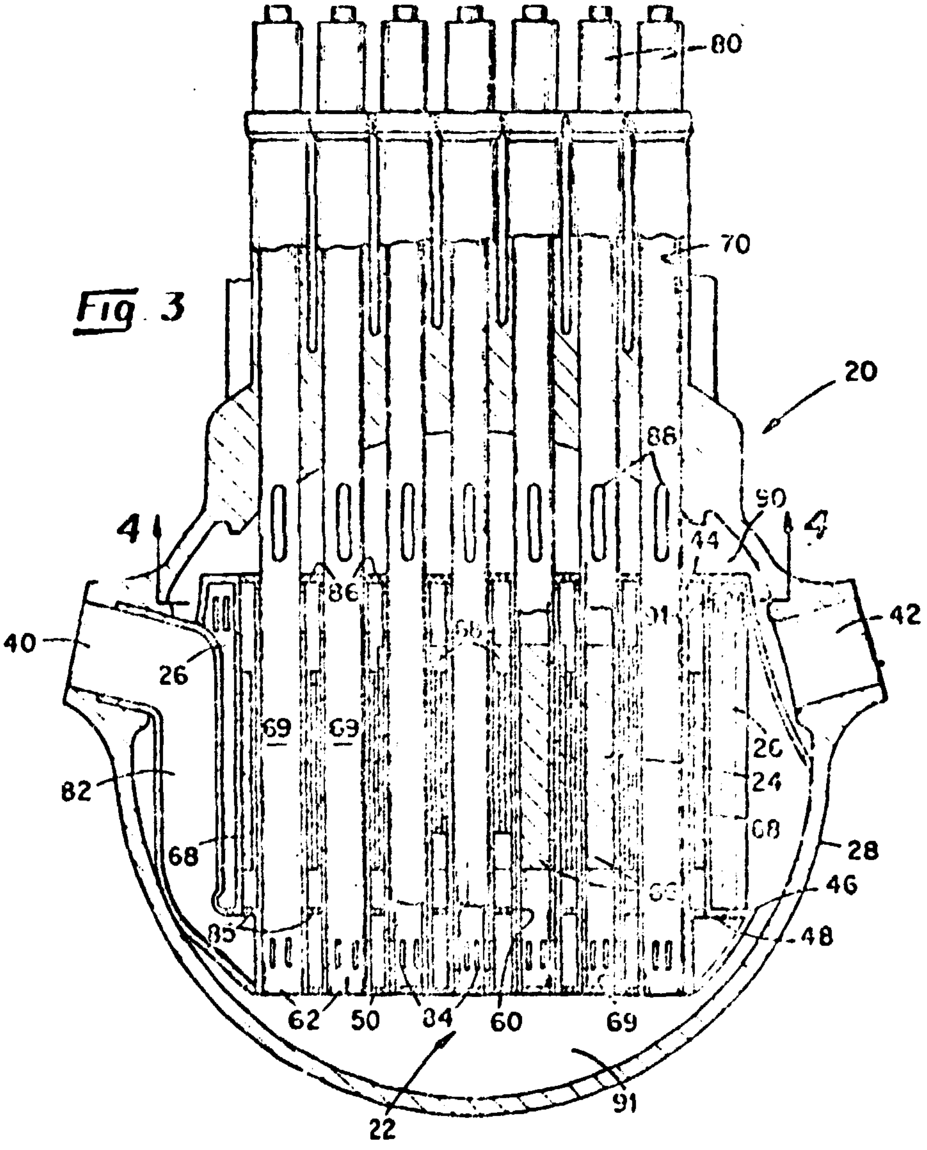

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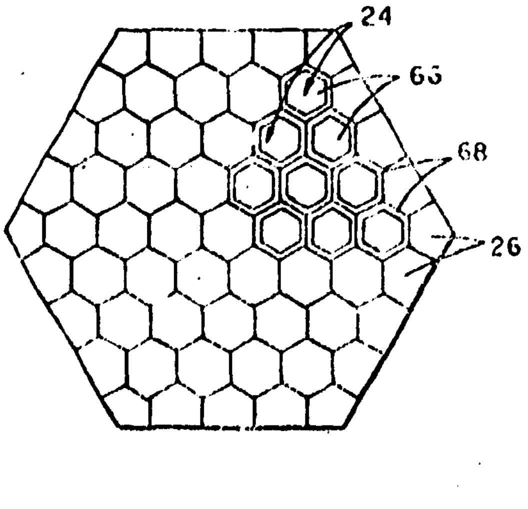
*Fig* 4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# Self-Induced Thorium Cycle in CANDU Type Reactors

by A. Radkowsky

The feasibility of utilizing the thorium cycle in the CANDU Heavy Water Pressure Tube Reactors has been investigated by the Chalk River Nuclear Laboratories. Two proposals have emerged. The first would require a thorium fueled reactor to be started off with plutonium excracted from fuel discharged from CANDU reactors on the uranium cycle. As the thorium built up, U-233 would be extracted and fabricated into thorium-U-233 fuel elements. At each reloading there would also have to be some plutonium added, since not enough U-233 would be produced. The Canadians have stated that this proposal might be economical when the price of uranium ore exceeds $ 100 per pound, more than three times the present cost.

The second Chalk River proposal is the Self-Sufficient Thorium Cycle. In this case the purity of the heavy water would have to be increased to 99.75% and the power density of the core decreased, among other attempts to attain extremely good neutron economy. In this case enough U-233 would be produced at each refueling to permit reloading the core, taking into account losses in reprocessing and fuel fabrication. Since natural thorium has no fissile fuel, it would be necessary to start off with a loading of highly enriched U-235, greater in quantity than conventional light water PWRs, and requiring much more separative work. The Canadians state that this proposal would not be economical until the price of uranium ore was far above $200. per pound.

These studies were all done before the movement to emphasize non proliferation and use of denatured fissile fuels, that is isotopic mixtures of uranium fissile fuel and U 238, such that U-235 content is less than 20% and U-233 content is less than 12%.

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The use of denatured fuels would hurt performance on the thorium cycle, although there would still be significant reductions in uranium ore usage. In all probability the self-sufficient thorium cycle would not be realized. The addition of some U-238 to the fuel results in the formation of Pu-239 which generally has an effective valve of eta of less than 2, and thus would impair breeding.

Undoubtedly a large part of the cost figures given by the Canadians are due to the very costly refabrication and reprocessing cost of U-233. U-233 contains some U-232 which decays into isotopes having very high gamma activity, so that all work involving U-233 must be done remotely with heavy shielding. Due to the activity of Protactinium -233 irradiated thorium fuels require a cooling period of a year, instead of only 150 days as is the case for uranium fuels. The activity of thorium itself is so high that it must be stored for ten years before possible reuse.

In contrast the self-induced thorium cycle will require no reprocessing whatever, and no increase in heavy water purity. The power capability may actually be increased instead of decreased. The cycle will not be completely self sufficient, about 10% of the fuel will have to be natural uranium. The thorium will be irradiated to a burnup of 20,000 MWD/T. This will still be a tremendous gain in uranium utilization, and the thorium supplies will be adequate for many centuries.

Life history studies have indicated that the self-induced process operates quite rapidly and the entire transition to the thorium cycle could be done in five years. Moreover a new technique has recently been found which could cut the changeover period to about two years. This would be still without any reprocessing or boosters.

The only disadvantage would be the need for removal of individual fuel pins.

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At present these are welded, but our engineers have worked out a simple method for removal and replacement. Even with the Chalk River proposals it is also necessary to work out a method of removing pins for reprocessing.

The self-induced thorium cycle takes advantage of the inherent characteristics of the CANDU cycle. It does not appear that any significant modifications to the core design would be necessary. The cost savings would be vast over the need to extract and fabricate U-233 and plutonium fuel elements. Also, there would be no concern about proliferation since there would never be any fissile material in free form.