Committee I
The Nuclear Option in the Past,
Present and in the Future

DRAFT--6/15/92
For Conference Distribution Only

SAFETY ASPECTS OF REACTOR TYPES AND IMPLICATIONS FOR NUCLEAR FUEL SUPPLIES

by

Alvin Radkowsky
Professor of Nuclear Engineering
Tel-Aviv University
Tel-Aviv, ISRAEL

The Nineteenth International Conference on the Unity of the Sciences
Seoul, Korea August 19-26, 1992

Safety Aspects of Reactor Types and Implications for Nuclear Fuel Supplies

Alvin Radkowsky
Professor of Nuclear Engineering
Tel-Aviv University

Abstract

The revival and expansion of nuclear power seems inevitable, given the steady rise worldwide in electric power consumption. Sharp increases in electric power needs may be anticipated as a result of the trend towards electric automobiles. This makes sense only if the increases are met by nonpolluting sources, meaning, for the foreseeable future, nuclear power.

The expansion of nuclear power may, however, be held up by public apprehension as to (1) safety of nuclear power plants and (2) a link between nuclear power and the proliferation of nuclear weapons, and especially the possibility of nuclear weapons terrorism. So far these issues have not been addressed, except for a design effort to incorporate passive safety features in case of a loss-of-flow accident. Another potential

hazard, which fortunately has not yet resulted in an

accident,is the use of soluble boron control. Small boron leaks have been found to corrode high strength steel parts and to impede valve operation.

The concern as to nuclear weapons implications arises from the fact that a one gigawatt-electric light water reactor (LWR) discharges annually approximately 200 kg. of plutonium in its spent fuel. An increase of nuclear power generation equivalent to one-quarter of the global level of fossil fuel use would result in the production of 500,000 kg. of plutonium a year. This is bad enough but at least this type of plutonium requires considerable expertise to produce a nuclear explosion. A much greater threat is presented by the probability that concerns as to uranium supply will lead to the development and deployment of Liquid Metal Cooled Fast Beeder Reactors (LMBR). If the projected increase in nuclear power is supplied by LMFBRs, approximately 5,000,000 kg. of plutonium of the finest weapons grade will be discharged per year. It would be extremely difficult to prevent diversion of some of this material. Moreover sodium cooled reactors have been found to have extremely high capital costs and difficult to keep in operation.

In this paper we present two reactor core concepts which can largely overcome the above cited problems. These will be replacement cores, suitable for installation in present light water plants.

The first is the High Gain Light Water Breeder on the Uranium-Plutonium cycle. A breeding gain of well over 10% in 6 years is feasible, yet most of the plutonium is standard light water reactor grade, difficult to use for weapons.

The second is the Light Water Nonproliferative Thorium Reactor, in which virtually no material suitable for weapons is produced. About 80% of the energy is obtained from thorium and, since thorium is much more plentiful than uranium, adequate nuclear fuel supplies for several centuries are assured.

These concepts also possess superior safety characteristics. Neither of these concepts requires the use of soluble boron control. Each has strongly negative moderator and void temperature coeffcients of reactivity, and scram is much faster than in conventional LWRs. Passive safety features now under developmemnt can be incorporated.

Text of Conference Paper

The revival and expansion of nuclear power seems almost inevitable, given the steady rise worldwide in electric power consumption. The trend towards electric automobiles, already mandated in California, will probably soon result in a sharp increase in the need for electric power generation. This makes sense only if the increase is met by nonpolluting sources meaning, at least for the foreseeable future, nuclear fission power. Other motivations for nonpolluting sources are concerns about the global greenhouse warming and acid rain.

The expansion of nuclear power may, however, be held up by public apprehension as to (1) the safety of nuclear power plants and (2) a link between nuclear power and the proliferation of nuclear weapons, especially the possibility of nuclear weapons terrorism.[1] So far these issues have not been addressed, except for the development of passive safety cooling features in case of a loss-of flow accident.

As regards safety, there are a number of remaining problems. A potential hazard, which fortunately has not yet resulted in an accident, is soluble boron control in the core coolant. The U.S. Nuclear Regulatory Commission has reported that small boron leaks have been found to corrode high strength steel parts in pumps and coolant nozzles and to impede valve operation.[2,3] Also, there is always the possibility that the emergency coolant supply may be left unborated, which could result in a reactivity accident.

Another questionable feature is the use of cluster control rods, terminating in typically twenty or more 1-cm. diameter absorbing pins. A distortion of a single pin could prevent insertion of the entire control rod.

The concern as to nuclear weapons implications arises from the fact that a one-gigawatt light water nuclear power reactor (LWR), the dominant type in most of the world, discharges approximately 200 kg. of plutonium annually in its spent fuel, enough for more than twenty nuclear weapons. If we suppose an increase in nuclear power generation equal to one-quarter of the present global level of fossil fuel use, the nuclear fuel capacity would reach 3000 GW Thermal. Using present type reactors, a nuclear capacity of this magnitude would discharge over 500,000 Kg. of plutonium a year. This is bad enough, but at least the plutonium is high in the content of the plutonium-240 isotope, and therefore requires considerable expertise to produce a nuclear explosion.

A much more serious problem arises from the fact that present cores utilize only a few per cent of the potential energy of natural uranium. Concerns as to the adequacy of natural uranium supply for such a high level of nuclear power generation will lead to pressures for the development and deployment of Liquid Metal Cooled Fast Breeder Reactors (LMFBR). In such reactors plutonium bred in the reactor core is routinely separated from spent fuel in nuclear fuel reprocessing plants and recycled in fresh reactor fuel. A 3000 GW Thermal nuclear power generating system based on LMFBRs will produce approximately 5,000,000Kg. of separated plutonium a year. Moreover this plutonium will be of the finest weapons grade, very low in plutonium-240 content. It is difficult to envision administrative controls capable of safeguarding completely such large amounts of weapons grade plutonium against diversion of significant quantities into nuclear weapons and into potential use for nuclear terrorism.

It must also be mentioned that nuclear power based on the use of LMFBRs will be extremely costly, at least according to limited experience with the SUPERPHENIX. Captital costs have been about twice that of light water nuclear power plants, and maintenance difficulties have limited operation to 10% of the time. Such difficulties were predicted by the late Admiral H. G. Rickover, based upon operational problems with the SEAWEOLF, the second nuclear submarine, which was initially sodium cooled. With a light water plant the reactor compartment can be entered a few seconds after shutdown; with a sodium plant, it was necessary, because of the high gamma activity of the sodium, to wait for six weeks. Furthermore shutdown was almost precluded for the Seawolf plant, because the sodium coolant would have frozen. There are also the well known problems of sodium-to-water heat exchangers, which are an order of magnitude more severe than that of water-to-water heat exchangers. These difficulties are inherent with the use of sodium coolant, although LMFBR engineers are endeavoring to design methods of alleviating them.

In order to overcome these many problems I have devised two new approaches to core design, utilizing proved light water technology. In each case the cores will be suitable as replacements in present light water plants, with minor alterations, such as change of the pressure vessel head. The cores will also, of course, find application in the hoped for greatly expanded nuclear power generation of the future.

The first of these concepts is the High Gain Light Water Breeder Reactor on the Uranium-Plutonium Cycle. The second is the Nonproliferative Light Water Thorium Reactor.
We now discuss each of these concepts.

The High Gain Light Water Breeder Reactor on the Uranium-Plutonium Cycle

Despite intensive efforts in many countries to design high conversion reactors with MOX fuel, it has proved very difficult to approach the break-even point. Control by conventional means is also problematic because of the high boron densities required in the cooling water with tightly spaced fuel lattices. There are also concerns as to the possibility of a positive void coefficient as a result of the large increase of the eta of plutonium-239 from the epithermal to the fast neutron energy region.

Actually if the plutonium cycle could be continued to higher isotopes, it is evident from Table 1 that a very satisfactory breeding gain could be obtained in a lattice with about 0.5 water to fuel volume ratio. The principal cause is the fact that in the epithermal energy region plutonium-241 has a very high value of eta, almost equal to that in the fast region, as is evident from Figures 1 and 2. This is in contrast to plutonium-239, which has a very low value of eta in the epithermal region. What prevents the continuation of the plutonium cycle to these higher isotopes is the formation of plutonium-240, a high resonance absorber, which rapidly reduces reactivity, necessitating refueling after modest burnups. The buildup of plutonium-240 in the MOX fuel is a two-step process. The uranium-238 transmutes into plutonium-239, which has a very high alpha in the epithermal region, and then forms large amounts of plutonium-240.

Our strategy is to make a transition from plutonium-239 to plutonium-241, while circumventing the adverse reactivity effect of the buildup of plutonium-240. To accomplish this we utilize two cores of equal power rating, a Prebreeder and a Breeder. Each core has a multiple seed-blanket arrangement. The geometry of the two cores is identical except that the Breeder seed has a lower water fraction than that of the Prebreeder. The function of the Prebeeder seed is to generate plutonium fuel with a relatively high fraction of plutonium-241 so that it can be fed into the Breeder seed, which has a harder spectrum and will therefore utilize the plutonium-241 more effectively. The blankets in each core are fueled with either natural uranium oxide, or MOX fuel, with an equivalent reactivity, in which the plutonium is that discharged from conventional light water reactors. In the Prebreeder the seeds are fueled with plutonium zirconium alloy plates or rods, the plutonium again being derived from light water core discharge. The blanket is subcritical, so that the core reactivity is controlled by the seed. Since there is no uranium-238 in the seed, no additional plutonium-240 can form there. A long burnup can be achieved in the seed because the reactivity loss due to depletion of the initial plutonium-239 and buildup of fission products is partially balanced by the depletion of the initial plutonium-240, which transmutes into plutonium-241. Furthermore the plutonium-240 in the seed fuel elements has a relatively high fission probability. Usually the fissioning effect in plutonium-240 is nearly suppressed by competition with its very high resonance capture. In our concept the plutonium-240, because of its high concentration in the seed fuel elements, has saturated resonances, resulting in less competition with fissioning, as exemplified in Figure 3.

The Prebreeder seed fuel loading is adequate for about one year of operation. The core is designed to have a fissile inventory ratio of about unity. After one year the seed fuel is reprocessed separately in order to remove fission products and then fed back into the Prebreeder seeds for three cycles. The reprocessed fuel from the Prebreeder seeds is then fed into the Breeder seeds where the tight lattice spacing and the high percentage of plutonium-240 and plutonium-241 result in a fission inventory ratio of over 1.08. The blanket fuel in both cores is always reprocessed separately and can be used to provide fuel for conventional PWRs. The recycling scheme is shown in figure 4.

Our calculated breeding gain is 10% in 6 years. This can be increased when an equilibrium cycle is approached with higher plutonium-240 content in the fuel fed into the conventiional light water cores. Because of the decay of plutonium-241, the breeding gain is very much dependent on the rapidity of recycling. Figure 5 illustrates this point. The British Fast Breeder group at Douneray has reported a three-month reprocessing and refabricating time for plutonium fuel. The fact that high gain breeding can be accomplished in a light water nuclear plant should provide an incentive for development of rapid reprocessing and return of the plutonium to the cores.

The initial fissile fuel loading for a 1000 megawatt-electric prebreeder core is about 3500 kg. The time between refuelings is more than one year, rather than every three months, as required in the case of the liquid metal fast breeder reactor(LMFBR), so that the fuel inventories are substantially reduced for our system. Thermal hydraulic analysis indicates that each of the two seed-blanket cores (Prebreeder and Breeder) can fit into the pressure vessel of a standard pressurized water reactor (PWR) and meet safety requirements. Major advantage of this concept are: the fact that good breeding gain can be obtained, yet the vast majority of the plutonium discharged will be high in plutonium-240 content, which cannot be utilized for weapons without considerable sophistication; the continued utilization of present light water plants and technology; and strongly negative moderator and void coefficients.

The Nonproliferative Light Water Thorium Reactor

This concept provides an economic approach to the utilization of the vast nuclear potential of thorium. None of the fuel materials used to load the core or discharged from the core can be used for nuclear weapons. Since thorium is at least three times as plentiful as uranium, adequate nuclear fuel supplies will be assured for several centuries, utilizing light water reactor technology.

Although the INFCE program concluded that thorium offered no attraction from either nonproliferative or economic standpoints, their studies were confined to obvious core strategies in which a large amount of nonproliferative uranium fuel (meaning that the uranium -235 content was no greater than 20%) was added to the thorium. It turned out that the amount of plutonium built up was less than in a standard LWR, but a large amount of uranium-233 was created, which, of course, has weapons potential. It was also necessary to extract the uranium-233, reprocess it, and fabricate it into fuel elements to be fed back into the core. This is very expensive because of the high gamma activity of the uranium-233. A recent ten-year (1979-1988) collaboration between Germany and Brazil reached the same conclusions.

Therefore we have adopted a completely different approach utilizing a special multiple seed-blanket arrangement. The seed regions are fueled with nonproliferative uranium (20% uranium-235 and 80% uranium-238) in zirconium alloy. The blanket fuel elements are of thorium oxide spiked with a few per cent of the same nonproliferative uranium oxide (20% uranium-235 and 80% uranium-238).

The seed regions have a very high water to fuel volume ratio. There are four reasons for this. First the use of such a high percentage of water results in an extremely thermal spectrum, which minimizes the capture in uranium-238, and results in a high value of the seed multiplication constant, which in turn tends to maximize the fraction of core power obtained from the blanket. Second the production of plutonium is minimized. Third with such a thermal spectrum what little plutonium is created will have a good chance of fissioning. Fourth the neutrons suppplied by the seed to the blanket will be thermal, rather than fast as in previous seed-blanket cores. This will reduce the number of seed neutrons required from the seed to the blanket because fewer of those neutrons will be captured by epithermal fission products and protoactinium. Every neutron captured by protoactinium is a double loss, the loss of a neutron and the loss of a prospective uranium-233 nucleus. It is true that the the fast effect of the neutrons from the seed will be reduced, but the fast effect is anyway very small in thorium. The seeds will be refueled every twelve or eighteen months, the same intervals as in conventional light water reactors.

The blanket water to fuel volume ratio will be about 1.5. The blanket will remain in place for about ten to twelve years and, by means of successive seeds, irradiated to the full metallurgical lifetime of over 100,000 MWD/T, as reported by Oak Ridge experiments, for thorium oxide rods containing a small amount of uranium.[5] The ability of thorium oxide to reach such high burnups is attributed to the fact that thorium oxide forms a strictly stochiometric lattice, in contrst to uranium oxide. Figure 6 shows that such thorium blankets, if properly designed, maintain a nearly steady value of the multiplication factor up to very high irradiations. Figure 7 illustrates the fact that even at such high irradiations thorium blankets continue to generate high energy output for a relatively small input of seed neutrons.

What is of great importance is that the energy from the thorium is obtained by burning in place the uranium-233 as it is formed. It is unnecessary ever to extract the uranium-233 and fabricate into fuel elements. Thus thorium can be utilized for production of nuclear energy without the need for a new fuel cycle and developing techniques for the fabrication of highly gamma active uranium-233.

The inclusion of a small amount of uraniun in the thorium oxide rods serves three purposes:

First to make the reactivity of the blanket when installed sufficiently high so that the blanket generates approximately the same fraction of core power throughout the blanket life. A natural thorium oxide blanket would have an initial multiplication factor of almost zero except for a very small fast effect, and would produce practically zero power.

Second to increase the energy obtained from the thorium for a given seed neutron input. It will be noticed from Figure 7 that for a given seed neutron input the increase in energy generated by the blanket for the spiked thorium over that from natural thorium is much greater than the energy worth of the uranium-235 added to the blanket. This is because adding fissionable fuel to the blanket is a much more efficient way of supplying neutrons to the blanket than getting them from the seed, especially as the seed fuel depletes and accumulates fission products. There are, of course, limitations imposed by the need to control the core from the seed regions and not to make the initial blanket power too high, or produce significant amounts of plutonium in the blanket.

Third to ensure that the small amount of remnant uranium-233 at the end of blanket life will not be usable for weapons. The uranium-233 will be denatured by being uniformly mixed with the initial uranium-238 (only a small part of which will be depleted), as well as uranium-232 and uranium-234 formed in the blanket. Thus the uranium-233 could not be used for weapons without isotopic separation, which is unlikely in view of the high gamma activity of the uranium-233.

According to our calculations about 80% of the core energy can be obtained from thorium. This will lead to about 50% or more reduction in fuel costs. Another gain will come from faster refueling time. In conventional light water cores, every fuel element assembly must be lifted and either discharged or relocated to another position in the core, as dictated by fuel management considerations. With our core concept the seed assemblies are simply removed and replaced by fresh seed assemblies, and the blanket assemblies are left in place.

The plutonium production rate is calculated to be about 1% that of a standard light water core. The seeds are replaced when about half of the initial uranium-235 is depleted, since it is necessary to maintain a high multiplication factor in the seed. Reprocessing of the seed fuel will be easy in view of the low plutonium content.

Further economic gains will result in both of our concepts from the elimination of the need for soluble boron control during operation. Not only will safety be enhanced but a complex system with extra piping, chemistry, and maintenance will be eliminated. With the seed-blanket core arrangement there is a strongly negative moderator coefficient, which will simplify load following.

Preliminary thermal analysis indicates that the same power density can be obtained in the Nonproliferative Thorium core as in a conventional light water core. Thorium oxide has a somewhat higher thermal conductivity than uranium oxide and the metallic seed fuel has much better thermal conductivity than ceramics.

Development of the thorium concept will ensure adquate supply of nuclear fuel for several centuries with enhanced safety and reduced fuel and plant costs without danger of proliferation.

Essential to both concepts described in this paper is the utilization of a nonparastic control system, which is mechanically very simple and results in much faster sram times than with conventional control rods. The elimination of parastic neutron capture enhances the breeding ratio of the High Gain Light Water Breeder on the Uranium-Putonium Cycle. For the Nonproliferative Light Water Thorium core the use of nonparasitic control considerably increases the fraction of core power obtained from the thorium.

In conclusion I believe that the exclusive emphasis at present in light water reactor development on passive safety arrangements to ensure survivability in case of a Loss-of-Flow Accident is inadequate.Much more attention should be devoted to developing core concepts which have additional enhanced safety features, improved economics, and the achievement of nonproliferation.

Notes:

1. Energy Policy July/August 1990 R.H. Williams and H.A.

Feiveson "Diversion-Resistance Criteria for Future Nuclear Power", pages 543-549.

2. NRC letter NB-6-108 Suppl. 2 of November 19, 1987

3. Nuclear News, January 1991, page 75

4. Nuclear News, December 1981, page 101

5. Olsen, A. R. et als. "Irradiation Behavior of Thorium Uranium Alloys and Compounds", ORNL, an IAEA Report

TABLE 1
Approximate Neutron Balance for Extended Plutonium Burnup

	Process	Neutron input	Neutron output
1.	One neutron absorbed in ^{239}Pu	1	η of ^{239}Pu = 1.90
2.	Include augmentation due to ^{238}U fast fissions (16% increase)		= 0.30
3.	Radiative capture in ^{239}Pu leads to the formation of 0.33 nuclei of ^{240}Pu		
4.	An additional neutron absorption in ^{240}Pu will result in:	0.33	
	10% of the ^{240}Pu = 0.03 nuclei fissioning		0.03 × 3.1 = 0.09
	16% augmentation by ^{238}U fast fissions		= 0.01
	90% of the ^{240}Pu will capture radiatively, producing 90% × 0.33 = 0.3 nuclei of ^{241}Pu		
5.	An additional absorption in ^{241}Pu will produce additional fission neutrons	0.30	0.3 × 2.40 (η of ^{241}Pu) = 0.72
6.	16% augmentation by ^{238}U fast fissions		0.11
Totals		1.63	3.13

Note: Excess neutrons = 3.13 − 1.63 = 1.50 neutrons per nucleus of ^{239}Pu.

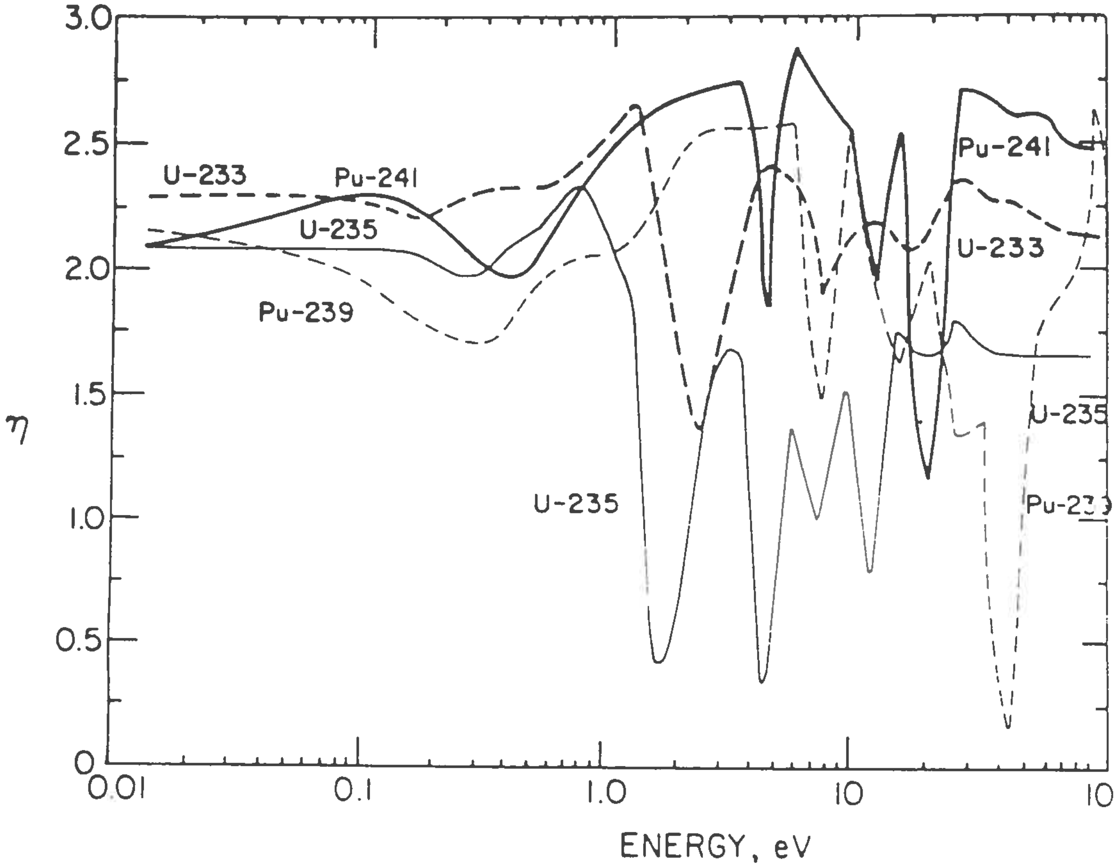

FIGURE 1:

(A) Values o η for fissile fuels as a function of neutron energy.

(B) values of η for fissile fuels as function of neutron energy (continued).

(See Following Figure)

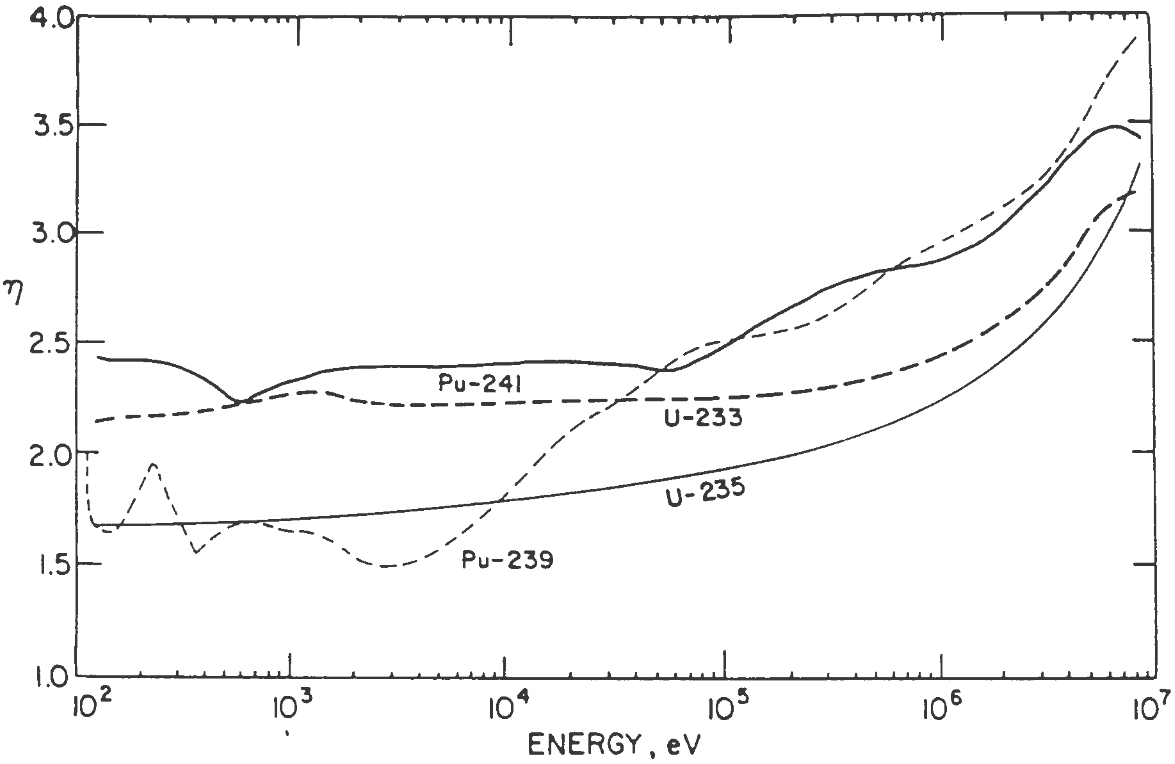

FIGURE 2.

Continuation of Figure 1

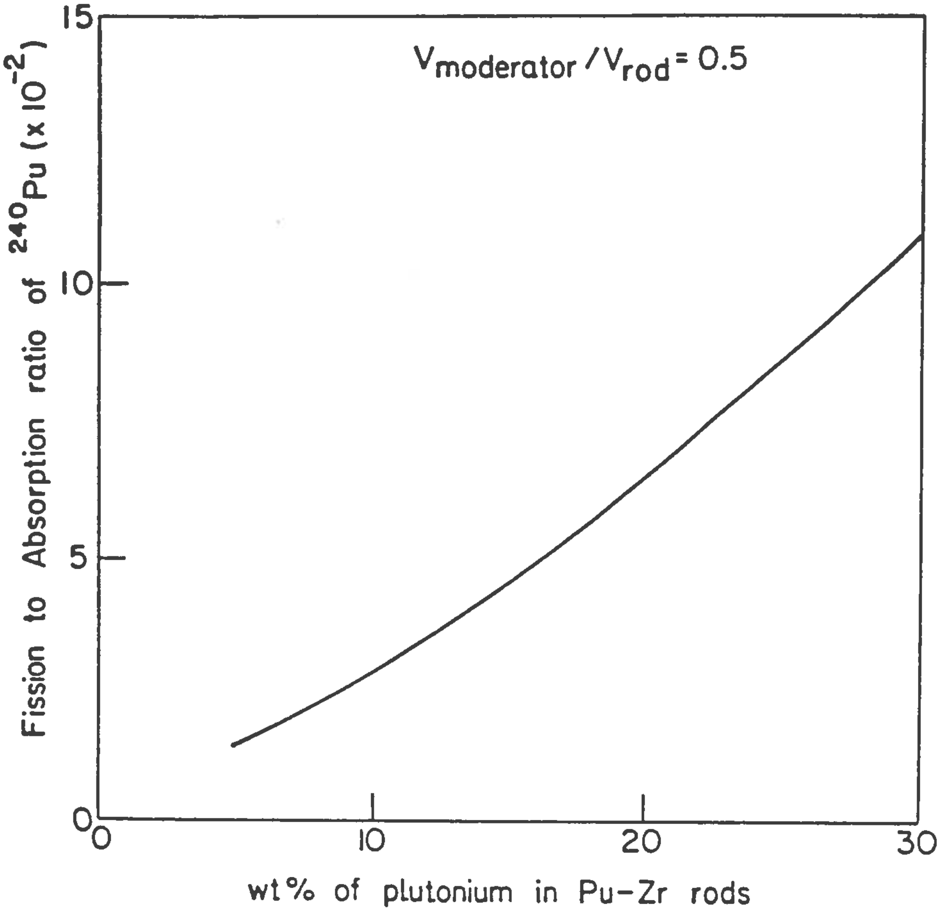

FIGURE 3:

The effect of weight percentage of plutonium on the fission-to-absorption ratio of ^{240}pu for ^{240}pu/^{241} pu=4.3.

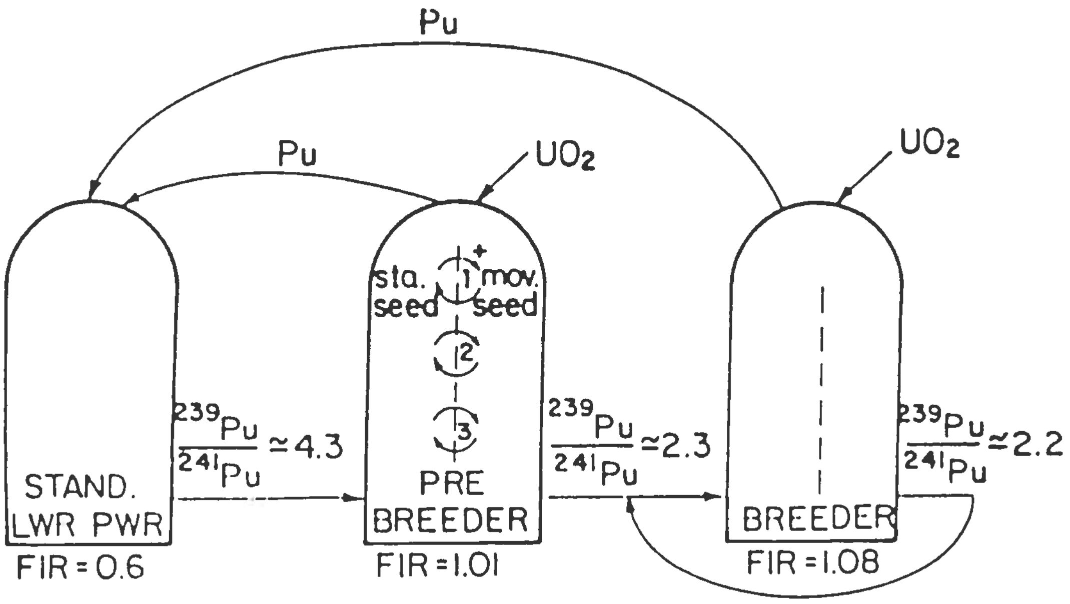

FIGURE 4:

Schematic description of HGLWBR fuel cycle (where the numbers which are given are typical values). += the fuel cycle number between moving seed and stationary seed.

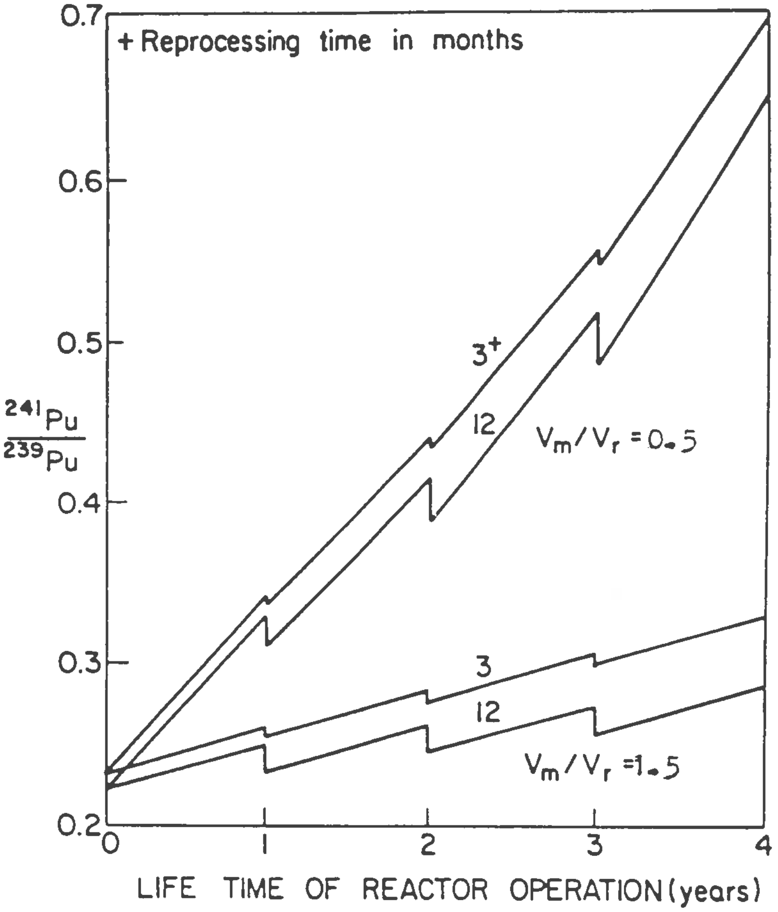

FIGURE 5:

The effect of reprocessing time on the atomic ratio of ^{241}Pu to ^{239}Pu

for the four fuel cycles(assuming 1 year EFPD reactor operation for each cycle).

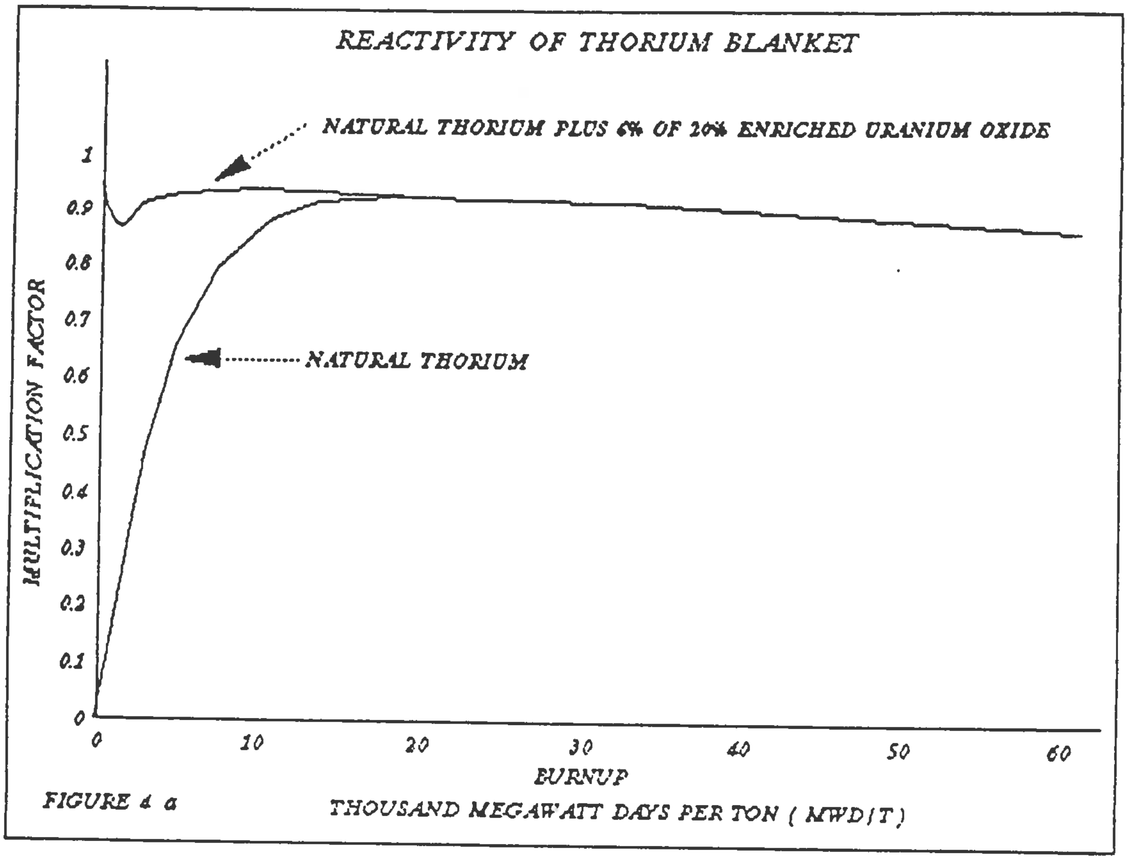
REACTIVITY OF THORIUM BLANKET
NATURAL THORIUM PLUS 6% OF 20% ENRICHED URANIUM OXIDE
NATURAL THORIUM
MULTIPLICATION FACTOR
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
BURNUP
THOUSAND MEGAWATT DAYS PER TON (MWD/T)
FIGURE 4 a

FIGURE 6.