Using thorium in a commercial nuclear fuel cycle: how to do it

The testing and first practical use of thorium in the fuel of commercial LWR cores, based on the Radkowsky Thorium Fuel Concept, is set to take place between 2002 and 2005. The aim is to show that current designs of LWRs can use a thorium fuel with improved performance and economics, while the world gains in reduced risk of further nuclear proliferation.

by ALVIN RADKOWSKY

The core of a power reactor using the thorium-based fuel known as RTF (Radkowsky Thorium Fuel) fits into exactly the same space as the cores of current standard uranium reactors, thus requiring only minor changes in the plant. The importance of this feature is evident - ensuring virtually no risk to the huge investments already made in the present LWR plants throughout the world.

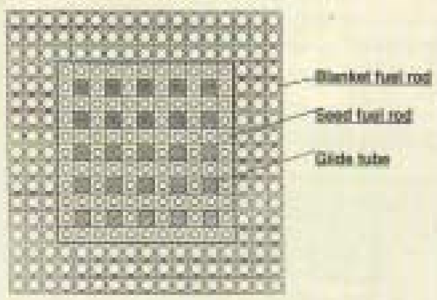
The RTF has the following advantages:

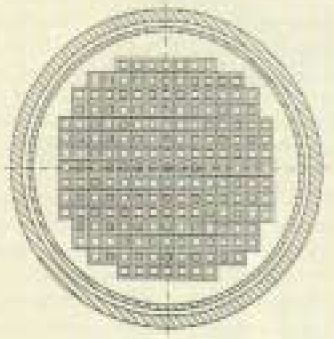
- RTF spent fuel is completely nonproliferative for all practical purposes. In contrast, standard uranium LWRs (1 GWe) discharge between 250 and 300 kg of plutonium. Only 5 to 7 kg of such plutonium, with the services of only 3-4 people, is sufficient to fabricate a bomb.
- There is a dramatic reduction in radwaste in quantity, toxicity, radioactivity and heat emission.
- Safety is enhanced due to the elimination of soluble boron control during operation. Otherwise, kinetic behaviour is similar to that of standard LWRs, and the core meets accepted thermal specifications.
- Natural uranium ore requirements are reduced by about 20%.
- Fuel cycle costs are reduced by 20% to 30%.
- There is no need for fuel reprocessing; the once-through cycle is optimal.
- The RTF is especially suited for burning and disposing of either weapons-grade or reactor discharge plutonium.

RTF is especially suited for burning and disposing of HUE from dismantled nuclear weapons.Radkowsky Thorium Power Corporation (RTPC) obtained initial funding from Raytheon Nuclear Inc and has arranged for a Department of Energy-USIC grant through Brookhaven National Laboratory to fund the Kurchatov Institute in Moscow. The plan is to construct lead test assemblies and test them in a VVER-1000 by the year 2002.

Ever since the Manhattan Project there has been interest in utilising thorium for nuclear power. Thorium is much more plentiful and cheaper than uranium; U-233, which is formed by neutron absorption in thorium, has the highest value of of all fissile nuclei in the spectra of LWRs. Thorium oxide, being stoichiometric, can withstand burnups as high as 100 GWd/t, much higher than uranium oxide. (1) The main difficulty is that natural thorium lacks any fissile component. Previous attempts to utilise thorium in LWRs have therefore required adding a fissile fuel homogeneously to the Th, the fissile fuels being either plutonium or highly enriched uranium (HEU), which "invest" neutrons into the Th in order to build up its reactivity. However, such fuels are expensive and highly proliferative. The RTF provides a practical and attractive solution to the utilisation of thorium by making use of the seed-blanket concept invented by Radkowsky and successfully demonstrated in the series of cores used in the Shippingport reactor. Indeed, had the nuclear cores in India been equipped with RTF, they could not have pursued their nuclear testing programme. The RTF core consists of seed-blanket units (SBUs), equal in

Seed-Blanket Unit geometry





PWRT core outlay with SBU assemblies

number and outer dimensions to the fuel assemblies of a standard uranium LWR.The basic idea of an SBU is to form two separate regions: the mainly thorium section, the blanket, which is the outer region of the unit, and in which the U-233 is burned in place; and the inner region, the seed, which consists of partially enriched uranium, the U-235 content being below 20%, a percentage generally accepted as being nonproliferative. The purpose of the seed is to supply neutrons to the blanket in the most efficient way by thermalising the seed spectrum (high water content) so as to minimise plutonium formation. This necessitates the use of metallic fuel, U/Zr, alloy in the seed, as in the first two Shippingport cores. The blanket fuel consists of oxide rods of Th plus a small amount of uranium enriched to less than 20%. The uranium is added for two reasons:

- Natural thorium has no fissile content; therefore enriched uranium is required to provide adequate power in the blanket during the period of U-233 buildup.
- The U-238 and other nonfissile isotopes denature the discharged blanket residual U-233 so that it cannot be used for weapons.

The RTF core design concept can in principle be used for all LWRs. Our initial work has concentrated on PWRs, of which there are two kinds, as shown in the figures: the Russian VVERs, which employ a hexagonal arrangement, and the Western PWRs having a square arrangement. We have completed a preliminary detailed design for the VVERT-1000 (3000 MWth output), the T standing for thorium, and are now working on a PWRT design. Optimisation of the seed and blanket lattice parameters was aimed at efficient generation and *in-situ* burning of U-233 (in blanket). This optimisation resulted in moderator-to-fuel volume rations (Vm / Vf) of 3.2 and 1.9 in seed and blanket regions, respectively. The relatively high Vm /Vf value in the seed was chosen in order to reduce the epithermal absorption of U-238 and consequently the buildup rate of Pu isotopes. The blanket Vm /Vf value was chosen as an optimal intersection point of two processes: U 233 buildup (low Vm /Vf) and efficient fission (high Vm /Vf). The resulting value of 1.9 was found almost identical to that of a standard PWR core lattice.

IN-CORE FUEL MANAGEMENT

One of the main features of the RTF is its incore fuel management scheme. The standard multibatch fuel management is replaced by a more complicated scheme, based on two separate fuel flow routes: blanket route and seed route. The residence time in the core of the SBU blankets is quite long (about 10 years) in order to achieve a very large accumulated burnup for the the fuel of about 100 GWd/t.

Basically, the incore management for the seeds is a 3-bath scheme, similar to that for standard uranium fuel assemblies. One-third of the seeds in fresh (F), one-third once burned (O), and one-third twice burned (T). After each annual (or 18-month) cycle the T seeds are replaced by F seeds. The F seeds together with the remaining partially depleted seeds are reshuffled into "empty" blankets so as to obtain a "low-leakage" configuration with optimum power distributions.The power density distribution across the core and the power density variation throughout a cycle are typical of that for a standard uranium PWR. Thorium oxide also has better thermal conductivity than uranium oxide and will be used in RTF blankets, where the power density is less than in standard uranium cores. According to Kurchatov Institute metallurgists, the endurance of zirconium-clad thorium oxide fuel can be enhanced by adding a small amount of niobium to the thorium.

REACTIVITY CONTROL SYSTEM

The RTF reactivity control system is based on the use of control rods (CR) and burnable poisons (BP) without the utilisation of soluble boron control. This is not unusual, as boiling water reactors are controlled in a similar manner.

The RTF cannot utilise soluble boron control during normal power operation because it would depress the power in the blankets too much. The blanket power is proportional to 1/(1 Kb), where Kb is the blanket multiplication factor and should be as close as possible to unity in order to maximise the thorium power output. Thus, it is necessary to control the RTF by BP and CRs in the seeds.Two types of BP rods are used in the current design in order to compensate for a major part of the burnup-related excess reactivity. The WABA type (Westinghouse Advanced Burnable Absorber) and Gadolinium loaded fuel rods. It was discovered that due to the close interaction of our SBUs, the standard PWR control rods, which are only about one-third the number of assemblies, are adequate to control the RTF. In all other seed-blanket core designs, a separate moving control means was required for each seed.

The WABA, presenting a standard PWR technology, is introduced to compensate the long-term burnup-related excess reactivity (from BOL to about 2/3 of cycle), and the Gd bearing rods to compensate for the excess reactivity of the first 30-50 days of the cycle. Our calculations indicate that the reactivity control requirements are almost identical for all cycles and that the total burn-up reactivity shift is about 5%p, about half of that for a typical uranium-fuelled PWR. Soluble boron will be used only for refuelling and for cold shutdown.

The NRC and EPRI have long been desirous of eliminating soluble boron control during hot pressurised operation in order to avoid small boron leaks, which may corrode high strength steel parts and impede operation of vital values. There is also the possibility of a reactivity incident if the emergency cooling water is not borated.

A complete 3-D calculation was performed for the reactor core during the power production cycle and following fuel discharge. The amount of natural U is about 20% less than for a standard PWR and the number of fuel rods about 25% less. These factors, together with a major reduction in back-end fuel storage expenses, result in an overall fuel cycle cost reduction of 20% to 30%.

The average annual U-235 discharge from the Radkowsky Thorium Fuel (RTF) is 128 kg, compared with approximately 750 kg of U-235 loaded annually into the core. Thus the seed U-235 is about 83% depleted and that of the blanket nearly 100%. The high burnup of the seed is due to the fact that most of the seed energy comes from burning U-235. As a result of the higher burnup, the RTF plutonium has far greater Pu-238 and Pu-242 content than that of a PWR (see Table 1). This effect is crucial in rendering the RTF nonproliferative for all practical purposes.

There are four factors involved in determining the proliferation resistance of the RTF plutonium:

- The amount of plutonium discharged per year is about 20% of that of a standard uranium-fuelled PWR.
- The critical mass of RTF Pu is greater than for PWR Pu.
- Because of the far greater spontaneous fission source in RTF Pu (see Tables 2,3), the nominal yield from a weapon is almost negligible and the chance of a fizzle yield is relatively high.
- Because of the much higher Pu-238 content of the RTF Pu than of PWR Pu (see Table 4), the heating in a weapon made of RTF Pu storage can be sufficient to cause a phase change in the Pu metal and disintegration of the explosive, resulting in extreme difficulty in fabrication and storage of the explosive device.

The total spontaneous fission source for a critical mass of PWR grade Pu is 7 times larger than that of a weapon-grade Pu. The RTF seed and blanket Pu is 13 and 22 times larger, respectively, than weapon-grade Pu. The nominal and fizzle yields are estimated for each of the considered Pu compositions and are presented in Table 2.

The probability that an explosion device, constructed from the RTF Pu, will deliver a nominal yield is small (seed) to negligible (blanket), and a probability of a fizzle yield is relatively high. Thus, it is shown that the RTF Pu will produce an unreliable weapon.

U-233 diversion potential

The RTF cycle is based on extensive utilisation of thorium, which produces through a nuclear reaction the fissile isotope U-233. U-233 has been determined to be superior to U-235 and at least as efficient as Pu-239 as a weapon material. Therefore, a special effort was invested in the RTF design to create effective barriers to diversion of U-233.

The total amount of U-233 in the spent blanket fuel, discharged once in 10 years, is about 630 kg (including Pu-233). The annual equivalent of 630 kg may represent a major proliferation potential. In order to eliminate this potential the U-233 created in the blanket is denatured by the initial addition of about 20% enriched uranium. The amount of U added for a dilution of fissile components was carefully chosen to reduce the overall content of fissile uranium isotopes in a discharged blanket fuel well below 17%, which is roughly equivalent to 20% of U-235 enrichment. Additional uranium isotopes created during the long in-core residence time of the blanket are U-232, U-234, U-235, and U-236.

Isotopic separation of the U-233 will be far more difficult and costly than the separation of U-235 from natural uranium. This is because of the several nonfissile isotopes mixed with the U-233 and contamination by the hard gamma emitter T1-208, which will necessitate remote operation. Thus there is no practical means to use the blanket discharge fuel for weapons.

Table 1. Discharged fuel fissile content (Pu) (fraction of total Pu)

Nuclide	PWR	RTF-Seed	RTF blanket	Weapons-grade	Super grade (Trinity)
Pu-238	0.010	0.065	0.120	0.00012	
Pu-239	0.590	0.465	0.382	0.938	0.98
Pu-240	0.210	0.225	0.150	0.058	0.02
Pu-241	0.140	0.155	0.147	0.0035	
Pu-242	0.050	0.090	0.201	0.00022	
Total Pu/yr (kg)	250	36.6	11.8		
Total HM/yr (kg)	26000	3206	4450		

Table 2. Probability of an indicated yield

Yield	Super grade (Trinity)	Weapons grade Pu	PWR grade Pu	RTF-seed grade Pu	RTF-blanket grade Pu
Nominal	0.88	0.68	0.07	0.006	0.002
Fizzle	0.02	0.06	0.35	0.55	0.74

Table 3. Spontaneous fission rate for Pu isotopes

Nuclide	Spontaneous fission rate (gm-sec)-1	Spontaneous fission source (kg-sec)-1				
		Super grade (Trinity)	Weapon grade	PWR grade	RTF seed grade	RTF blanket
Pu-238	2600.0	0	312	26×10^3	169×10^3	312×10^3
Pu-239	0.022	0.022	21	13	10	8
Pu-240	910.0	18700	52780	191.1×10^3	204750	137×10^3
Pu-241	0.049	0	0.2	7	8	7
Pu-242	1700.0	0	374	85×10^3	153×10^3	342×10^3
Total/kg of Pu	na	18200	53487	302×10^3	526×10^3	790×10^3
Total/critical mass	na	78.3×10^3	230×10^3	1611×10^3	3103×10^3	5135×10^3
Ratio to super grade	na	1	3	21	40	66

Table 4. Decay heat emission for different Pu compositions

Nuclide	Specific decay heat (watts/kg)	Weapons grade (watts/kg Pu)	PWR grade (watts/kg Pu)	RTF seed grade (watts/kg Pu)	RTF blanket grade (watts/kg Pu)
Pu-238	560	0	12.88	38.64	70.56
Pu-239	1.9	1.77	1.08	0.85	0.65
Pu-240	6.8	0.42	1.54	1.53	0.89
Pu-241	4.2	0.03	0.54	0.60	0.54
Pu-242	0.1	0	0	0.01	0.03
Total (watts/kg)	na	2.22	16.04	41.68	72.66
Total (watts/critical mass)	na	10	68	244	475