Thorium Fuel for Light Water Reactors - Reducing Proliferation Potential of Nuclear Power Fuel Cycle

by

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The proliferation potential of the light water reactor fuel cycle may be significantly reduced by utilization of thorium as a fertile component of the nuclear fuel. The main challenge of Th utilization is to design a core and a fuel cycle, which would be proliferation-resistant and economically feasible. This challenge is met by the Radkowsky Thorium Reactor (RTR) concept. So far the concept has been applied to a Russian design of a 1,000 MWe pressurized water reactor, known as a VVER-1000, and designated as VVERT. The following are the main results of the preliminary reference design:

- The amount of Pu contained in the RTR spent fuel stockpile is reduced by 80% in comparison with a VVER of a current design.
- The isotopic composition of the RTR-Pu greatly increases the probability of pre-initiation and yield degradation of a nuclear explosion.
- An extremely large Pu-238 content causes correspondingly large heat emission, which would complicate the design of an explosive device based on RTR-Pu.
- The economic incentive to reprocess and reuse the fissile component of the RTR spent fuel is decreased. The once-through cycle is economically optimal for the RTR core and cycle.
- To summarize all the items above: the replacement of a standard (U-based) fuel for nuclear reactors of current generation by the RTR fuel will provide an inherent barrier for nuclear weapon proliferation. This inherent barrier, in combination with existing safeguard measures and procedures is adequate to unambiguously disassociate civilian nuclear power from military nuclear power.
- The RTR concept is applied to existing power plants to assure its economic feasibility.
- Reductions in waste disposal requirements, as well as in natural U and fabrication expenses, as compared to a standard VVER fuel, provide approximately 20% reduction in fuel cycle cost.

The main challenge encountered in the design of a thorium based system is the necessity to supplement natural thorium with a pre-generated fissile component. Several design solutions were proposed and investigated, such as: initial start-up of the thorium cycle by enriched U, continuous addition of uranium as a fissile component to supplement self-generated U-233, reprocessing and recycling U-233, and addition of Pu to supplement self-generated U-233.

The improvement in natural uranium utilization by using thorium could be achieved only if the self-generated U-233 fissile material was separated and recycled into a closed fuel cycle. This approach, adopted by the LWBR, violated the non-proliferation requirement.

The RTR concept proposed by Professor A. Radkowsky offers a solution to the Th utilization problem. The basic idea is to use the heterogeneous, seed/blanket (SBU), fuel assembly. The Th part of the fuel assembly is separated from the U part of the assembly. This separation allows separate fuel management schemes for the thorium part of the fuel (a subcritical "blanket") and the "driving" part of the core (a supercritical "seed"). The design objective of the blanket is an efficient generation and in-situ fissioning of the U-233 isotope, while the design objective of the seed is to supply neutrons to the blanket in a most economic way, i.e. with minimal investment of natural uranium.

The SBU geometry provides the necessary flexibility to satisfy a major design constraint - full compatibility with existing pressurized water reactor (PWR) power plants. In addition, the heterogeneity of the SBU design allows the necessary (and separate) optimization of seed and blanket lattices. The design constraints are prescribed mainly by considerations of technical and economic feasibility. These constraints are imposed to support economic justification of the research and development activity required to design, verify, licence and implement the RTR fuel within a reasonably short period of time. The design constraints are summarized below:

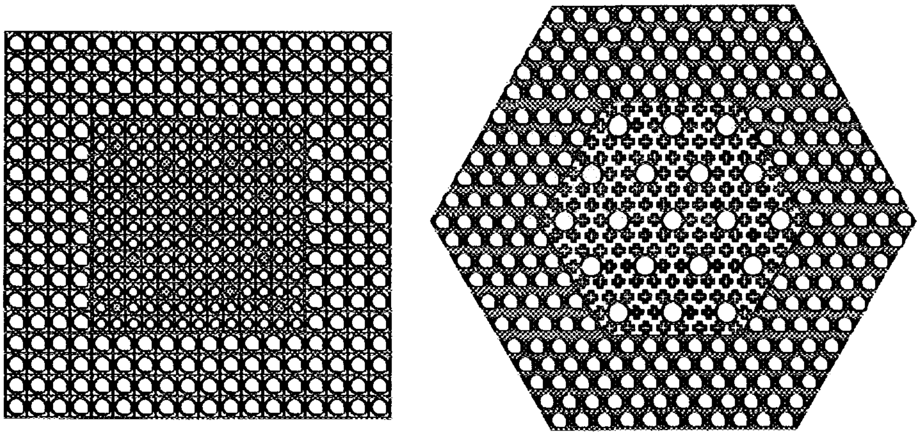
1. The RTR concept should be realized as a new fuel design, and thus, be completely compatible with existing power plants. Only minor plant hardware modifications, directly related to a different fuel assembly internal arrangement will be acceptable.
2. All safety and operational parameters of existing power plants will be preserved.
3. The fuel design will be based mainly on existing (not necessarily commercial) fuel technology. The maximum allowable fresh fuel enrichment will be kept below 20% of U-235 content.

The reference design of the RTR core and fuel cycle was carried out based on objectives and constraints discussed above.

The VVERT design is an implementation of a RTR fuel reload for a standard VVER-1000 core, where "T" stands for Thorium. The VVERT core is identical to an existing VVER-1000 core with 163 hexagonal fuel assemblies and 3,000 MWth power output. The average power density of 106 kW/l is somewhat higher than that of a similar PWR core of a western design. The hexagonal SBU and a corresponding square SBU (for the PWRT version) are shown in Figure 1.

The VVERT fuel assembly - SBU consists of two spatial regions: internal region (seed) and external region (blanket). The design objective of such arrangement is to maximize power production of the blanket region. The seed region volume and consequently its power share are minimized subject to two constraints: 1) total amount of uranium loaded in seed each cycle should sustain (drive) the subcritical blanket for a given inter-refuelling interval, and 2) the total surface of seed fuel should be adequate to sustain required temperature and heat flux values. The seed fuel was chosen as U/Zr alloy rods, which is consistent with fuel technology capabilities of the fuel vendor industry of Russian Federation (RF). The size of the seed rod and unit cell geometry were determined by consideration of neutronic and heat removal aspects as mentioned above.

The blanket fuel considered in present design was thorium oxide with addition of uranium oxide. The uranium was added to blanket fuel for two main reasons: 1) natural thorium does not include a fissile component, therefore enriched uranium is required to provide a reasonable power density in the blanket during the initial burnup period of U-233 gradual buildup, and 2) addition of U-238 assures that U-233 accumulated and discharged with the blanket fuel is sufficiently diluted to present no diversion (proliferation) potential.



PWRT SBU Assembly VVERT SBU Assembly

Fig. 1 VVERT SBU Geometry

The fuel cycle cost savings of approximately 20% may be derived from the Table 1 data. The amount of natural U per cycle is about 140 Mt compared with 170 Mt of a standard PWR, and the number of fuel rods fabricated is 11,000 compared with 15,000 rods per PWR annual reload. The fabrication cost of a metal alloy fuel rod (RTR seed fuel), produced by an extrusion process, is significantly lower than that of a PWR oxide rod. These three components of the front-end, as well as back-end savings in spent fuel storage expenses, results in a 20 to 25% reduction in an overall fuel cycle cost. This estimate is supported by a detailed fuel cycle cost calculation.

The basis for the back-end of cycle analysis is the amount (weight) and composition of the fuel discharged from the core. This fuel is discharged, stored and finally, disposed of in a permanent storage facility. Its fissile content, mainly amount and composition of Pu defines the proliferation potential of the fuel cycle. The isotopic composition of the spent fuel stockpile defines its radioactivity and heat emission levels, as well as the overall toxicity of the spent fuel as a function of time.

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Table 1: Fuel Cycle Data - Normalized to 1000 MWe Plant
(Comparison with "representative" PWR fuel cycle)

Fuel Cycle Transactions	PWR	RTR
Total Core Fuel Weight Mt H.M.	U = 80	U = 10 Th= 36
Average U Enrichment weight % U^{235}	3 - 4	20
Annual Fuel Reload Weight Mt H.M.	U = 27	U = 3.6 Th = 3.6*
Annual Natural U Requirement Mt H.M.	170	140
Annual Separative Work Requirement (enrichment) Mt S.W.U.	~160	~160
Annual Fuel Discharge Weight (Mt H.M.) : Volume (m^3) :	 27 ~8	 7.2* ~5
Annual Spent Fuel Storage/Disposal Cost**	$\$7x10^6$	$\$4x10^6$
Total Fuel Cycle Cost (arbitrary units)	1	0.75

Table 2: Discharged Fuel Fissile Content (Pu)
(fraction of total Pu)

Nuclide	PWR	RTR-Seed	RTR-Blanket	Weapon Grade(1)	super grade (Trinity)(1)
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/year (kg)	~250	36.6	11.8^c	-	-
Total H.M./year (kg)	26,000	3,206	4,450^c	-	-

Proliferation potential of a fuel cycle, or its proliferation resistance is defined by the quantity and the quality of the fissile material, which could be diverted to military use. An additional factor is the measure of complexity required to separate the fissile component from the normal material flow of the fuel cycle.

The assessment of proliferation potential depends to a great extent on the specific proliferation scenario. The scenarios related to a civilian nuclear power fuel cycle are national diversion scenarios, either clandestine or open. In both cases international treaties and safeguards may not be effective, because they can be abrogated and avoided. It is clear that in order to separate completely the development and expansion of nuclear power from the danger of nuclear weapon proliferation, international safeguards are necessary but not sufficient.

A decisive barrier to proliferation should be based on inherent properties of the fuel cycle itself. The fuel design should provide assurance that the quantity and quality of the fissile component of the fuel cycle material flow would reduce the proliferation potential below an acceptable threshold in the context of industrial capabilities and economic realities.

The quantity and the quality of the fissile material contained in the RTR spent fuel stockpile is compared with that of a standard PWR cycle. The proliferation potential of a material is assessed qualitatively following a simple model of reference 1.

The fissile material weapon quality is evaluated by considering three properties:

1. The critical mass. A critical mass is different for different isotopic composition of Pu and U.
2. The weapon yield degradation due to pre-initiation caused by spontaneous fission neutrons.
3. The weapon stability derated by heat emission.

The spontaneous fission source (SFS) defines an important characteristic of the weapon material, namely the yield degradation. Neutrons released by spontaneous fissions cause pre-initiation, i.e. the start of the explosion before the device reached its highest supercriticality value, which in turn causes a reduction of the device yield. A simple qualitative model described in reference 1 is used to estimate the yield degradation of the explosion device based on RTR Pu and to compare it with PWR grade Pu and weapon grade Pu.

The smallest value of the explosion yield results from pre-initiation, which occurs at the same moment when a device becomes critical. This, smallest yield, designated as “fizzle” yield, is estimated as 0.027 of the nominal yield.

A qualitative information published in an open literature with regard to expected performance of the Trinity explosion device (1) allows an estimate of the probabilities of the nominal yield and the fizzle yield. The relevant data for all considered Pu compositions is summarized in Tables 2 and 3. The first column shows a spontaneous fission source for one gram of a given isotope. The rest of the table shows the SFS in neutrons/sec for a critical mass of all considered Pu compositions. The last row presents the value of N, i.e ratio of a SFS for a given Pu composition to that of a weapon grade Pu, assumed for a Trinity 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, and for the RTR seed and blanket Pu is 13 and 22 times larger respectively. The nominal and fizzle yields are estimated for each of the considered Pu compositions and are presented in Table 4.

The probability that an explosion device, constructed from the RTR 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 RTR Pu will produce an unreliable weapon.

An additional barrier for a possible diversion of a reactor grade material is the heat emitted by its isotopes. The thermal power produces an increase of the temperature of a device and causes two effects: one is a temperature increase of metallic Pu, which undergoes a metallurgical phase transition at 115°C, and second is an overheating of a high explosive around the Pu core, which may cause the disintegration of this high explosive. The specific heat produced by different Pu isotopes is summarized in Table 5 and is used to estimate the total heat produced by a Pu metal critical mass in each case.

Table 3: Spontaneous Fission Rate for Pu Isotopes

nuclide	spontaneous fission rate $(\text{gm-sec})^{-1}$	spontaneous fission source $(\text{kg-sec})^{-1}$				
		super grade (Trinity)	weapon grade	PWR grade	RTR- Seed grade	RTR - Blanket grade
Pu-238	2,600.0	0	312	$26\text{x}10^3$	$169\text{x}10^3$	$312\text{x}10^3$
Pu-239	0.022	0.022	21	13	10	8
Pu-240	910.0	18,200	52,780	$191.1\text{x}10^3$	204,750	$136\text{x}10^3$
Pu-241	0.049	0	0.2	7	8	7
Pu-242	1,700.0	0	374	$85\text{x}10^3$	$153\text{x}10^3$	$342\text{x}10^3$
total/kg of Pu	-	18,200	53,487	$302\text{x}10^3$	$526\text{x}10^3$	$790\text{x}10^3$
total/critical mass	-	$78.3\text{x}10^3$	$230\text{x}10^3$	$1,661\text{x}10^3$	$3,103\text{x}10^3$	$5,135\text{x}10^3$
ratio to super grade	-	1	3	21	40	66

Table 4: Probability of an Indicated Yields

Yield	super grade (Trinity)	weapon grade Pu	PWR grade Pu	RTR - seed grade Pu	RTR - blanket grad Pu
Nominal	0.88	0.68	0.07	0.006	0.0002
Fizzle	0.02	0.06	0.35	0.55	0.74

Table 5: Decay Heat Emission for Different Pu Compositions

nuclide	Specific decay heat (watts/kg)	weapon grade (watts/kg Pu)	PWR grade (watts/kg Pu)	RTR seed grade (watts/kg Pu)	RTR 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	1.58	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)	-	2.22	16.04	41.68	72.66
total (watts/critical mass)	-	10	88	244	475

It is shown that the total heat produced by the RTR seed and blanket Pu is much higher than that produced by the PWR grade Pu. Heat loads at the level of seed and blanket Pu are likely to require special heat removal measures to be incorporated in the design of a weapon. The nature and effectiveness of such measures is beyond the scope of this paper, but it is reasonable to assume that the device stability will be impaired.

The RTR generated spent fuel stockpile will still require a safeguarded disposal facility, but taking into account the reduced quantity and quality of the fissile material, the combination of safeguards and inherent fuel cycle parameters can provide an adequate answer to the problem of weapon proliferation potential of nuclear power.

References

1. J. C. Mark, “Explosive Properties of Reactor-Grade Plutonium”, Science & Global Security, 4, 111, 1993.