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Review of the Radkowsky Thorium Reactor Concept[a]

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A novel reactor-design concept termed the Radkowsky Thorium Reactor (RTR) has been developed that shows potential for early application in conventional pressurized water reactors (PWRs). The RTR concept makes use of a seed-blanket geometry with thorium as the fertile material, and uranium of less than 20 percent enrichment as fuel in both the seed and blanket regions. About 163 seed-blanket units are employed in a 1,000 MWe RTR, and fuel shuffling during refueling is used to maintain an acceptable power distribution and a relatively-low critical mass. Other key features of the RTR are: (1) irradiating the blanket fuel of mixed ThO_2 and UO_2 for a period of 10 years prior to removal, and (2) employing metallic uranium-zirconium-alloy as the seed fuel and irradiating it for 3 years. The high fuel burnups of both the blanket and seed fuels relative to that in a conventional PWR results in a substantial decrease in the plutonium present in RTR spent fuel, and to substantial increases in the percentages of Pu-238, Pu-240, and Pu-242 in that plutonium. The RTR reactor design features are very similar to conventional PWRs, such that application of the general seed-blanket arrangement could be implemented rather quickly if there were no reactor safety, technical, or economic concerns.

In this review, the RTR is compared with a PWR considering key technical, safety, and economic features. Both reactors are operated with yearly refueling. Emphasis is on weapons proliferation resistance, fuel cycle costs, the comparative use of uranium and thorium fuel cycles, ability of the blanket fuel to be exposed for 10 years in an RTR environment, performance of RTR metallic seed fuel, and fuel shuffling/handling concerns. Relative to the PWR, the RTR shows a substantial increase in proliferation resistance to weapons production due to the low quality of the plutonium produced and to its lower production rate. However, PWRs operating on the once-through uranium cycle are considered to have adequate proliferation resistance.

Fuel-cycle-cost items were: fuel fabrication, natural uranium and thorium mining, Separative Work Units (SWUs) for fuel enrichment, fuel fabrication losses, chemical conversions, storage of fuel at the reactor site, and transporting fuel from the reactor to a storage/disposal location. Based on the reference conditions employed, the total fuel cycle costs of the RTR were 96 percent that of a conventional PWR. An important contribution to that result was the relatively-low cost estimated for transporting/handling RTR fuel to an "away-from-reactor" storage/disposal location; when such transporting/handling costs were not included, the RTR fuel cycle costs were 103 percent that of the PWR. The above differences in costs are small compared with uncertainties in cost parameters.

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a The review is based foremost on the article by Alex Galperin, Paul Reichert, and Alvin Radkowsky, published in *Science and Global Security*, Volume 6, (1997), pp. 265–290.

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Replacing the thorium with natural uranium will probably lower the RTR fuel cycle costs, and probably retain desirable non-proliferation features.

Overall, significant fuel and fuel-shuffling R&D/Demonstration is required before the viability of the RTR concept can be assured. Primary concerns are: (1) the practicality of exposing zirconium-alloy-clad fertile fuel rods for very long times (~10 years) and high burnups (~100 MWd/kg) to a high-temperature water environment containing small amounts of hydrogen; (2) the safety of metallic seed fuel having very high burnup (>150 MWd/kg) and high average seed power density (140 percent that of the PWR) when exposed to accident conditions; and (3) the impact on plant availability of extensive fuel shuffling of Seed-Blanket Units (SBUs) combined with removing fully-spent seeds from SBUs and reloading them with fresh seeds.

INTRODUCTION

The Radkowsky Thorium Reactor (RTR)[1] concept is one of the latest in a series of Thorium Seed-Blanket Reactor designs innovated by Professor Radkowsky. The original seed-blanket reactor was the Shippingport (Pennsylvania) reactor design for Light Water Reactors (LWRs) developed in the 1950s by the Naval Reactors Division of the US Atomic Energy Commission (USAEC) under Admiral Rickover; Radkowsky was a key member of Rickover's staff at the time. Changes in the original Shippingport design resulted in the Light Water Breeder Reactor (LWBR) utilizing U-233 as the fissile fuel in the "seed" regions, and thorium in the "blanket" regions. The purpose of the LWBR was to demonstrate fuel "breeding" in an LWR with fuel recycle, an objective that was attained with a "breeding ratio" of about 1.01.[2] More recently, with nuclear proliferation an issue and fuel recycle not acceptable, emphasis was placed on thorium seed-blanket modifications that would facilitate both increased proliferation resistance and early application in LWRs. A recent design and its performance and application are summarized in reference 1, which is the subject of this review.

THORIUM AND URANIUM FUEL CYCLES

Present-day commercial LWRs employ the "once-through" low-enriched uranium fuel cycle because that cycle has attractive economic performance. However, both thorium and uranium fuel cycles have been considered since the early days of power reactor development, and a number of thorium-cycle reactor concepts have been developed. Comparative studies of reactors employing thorium as the fertile material versus reactors using uranium have also been performed (it should be noted that the term "thorium cycle," which strictly applies to the use of thorium and U-233, is often used for convenience even when it is the thorium-uranium cycle—a mixed cycle—that is being considered).

An early comparative evaluation of various thermal reactors employing different fuel cycles was conducted by Rosenthal *et al.*[3] in 1965, and a summary of advanced converter reactor evaluations was issued by the USAEC in 1969.[4] Thorium use in power reactors was summarized in a report issued by the USAEC in 1969;[5] that report was a compilation of the thorium reactor studies given in references 3 and 4, along with additional information. The above reports considered Pressurized Water Reactors (PWRs) as the "standard" reactor against which other reactors were to be compared, and concluded that PWRs and Heavy Water Reactors (HWRs) were more economic employing the uranium cycle, and that the thorium cycle was preferred in High Temperature Gas Cooled Reactors (HTGRs) and Spectral-Shift (D_2O/H_2O moderated) Converter Reactors (SSCRs). An overview of the use of thorium in power reactors was written by Kasten[6] in 1970, covering LWRs, HWRs, HTGRs, molten-salt graphite moderated reactors (MSRs), and sodium cooled fast reactors. For reasons given below, the thermal reactors preferring the thorium cycle were HTGRs and MSRs.

In the 1970s, another series of reactor evaluations took place in association with the International Nonproliferation Fuel Cycle Evaluation (INFCE), with emphasis on once-through fuel cycles. Shapiro *et al.*[7] reported that while the thorium cycle would realize an increase in energy output per mined ton of uranium over that from the once-through uranium cycle in a conventional PWR, it was not economically attractive. The savings in the demand for uranium ore and the increase in fuel utilization occur relatively-late in plant life, while the early years' demand for uranium and separative work are high compared to values for the once-through uranium cycle. A study by Kasten, Homan, *et al.*[8] pointed out that while LWRs provide the most direct route for application of the thorium fuel cycle, the uranium cycle in LWRs was more economic under reference conditions. Of the reactors considered, only the HTGR was more economic on the thorium cycle, with fuel recycle. Without fuel recycle, all conventional thermal reactors tend to prefer the uranium cycle.

The seed-blanket reactor concept was not included in the above comparative evaluations, other than implicitly knowing that operating a "commercial" LWBR as a break-even breeder requires a very high cost for the U-233 inventory and for fuel recycle, making it non-competitive. No consideration was specifically given to the seed-blanket concept employing the thorium or the uranium cycle under conditions of once-through fuel cycles and relatively-low fuel conversion ratios. RTR type reactors are relatively recent and have not been independently evaluated concerning their preferred fuel cycle. However, it is not assured that the seed-blanket concept will prefer the thorium cycle.

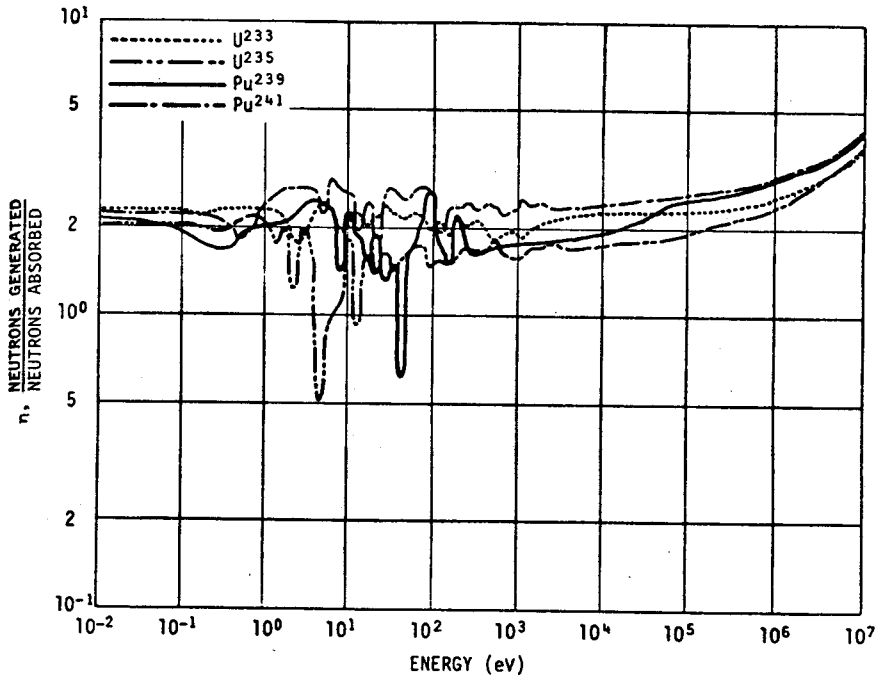

Figure 1: Value of η for various fissile fuels as a function of neutron energy.[9]

Features of thorium and uranium fuel cycles in thermal reactors are given below. In general, use of the thorium cycle in thermal reactors will be determined by the ability to generate, in economic reactor types, competitive cost nuclear power in comparison with the uranium cycle. The primary advantage of the thorium cycle is associated with the relatively high η (neutrons generated per neutron absorbed) of U-233, as illustrated in Figure 1, which compares η values of the various fissile fuels as a function of neutron energy. As shown, the η of U-233 at thermal energies is higher than for U-235, Pu-239, and Pu-241, although that for Pu-241 is very close in value. As a result, the

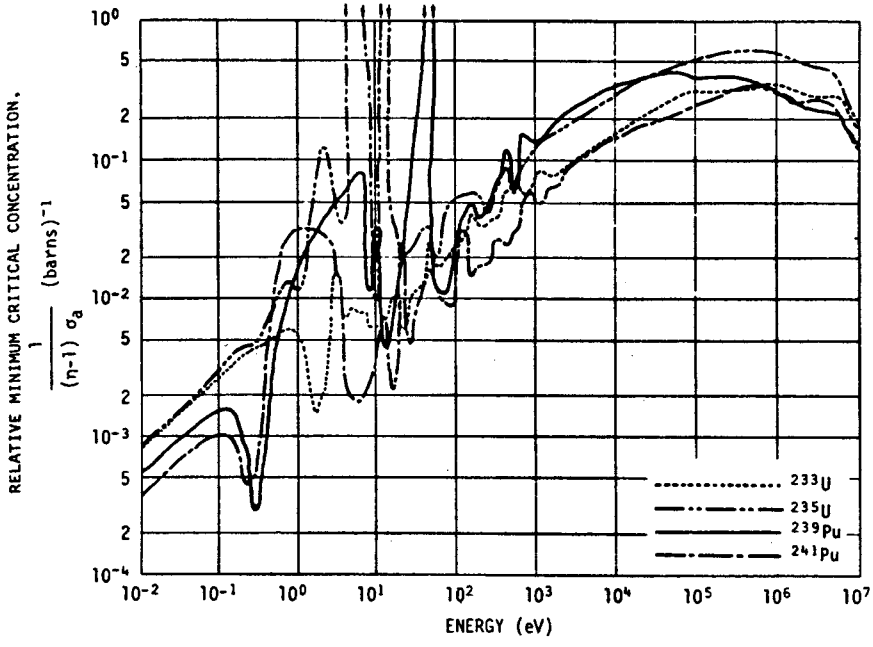

Figure 2: Relative critical mass of various fissile fuels.[10]

potential breeding ratio, η-1, is highest in thorium thermal reactors, which in the long term tends to keep the fissile content relatively high in the thorium fuel. This does not infer that the critical mass is relatively low, and in fact, the absorption cross section of U-233 is lower than for U-235, such that the U-233 concentration required in order to generate a given power level is about theme as for U-235, as given below.

The critical mass of fissile fuel has a direct influence on fuel inventory costs. A measure of critical mass is given in Figure 2, which plots the inverse of $(\eta\text{-}1)\sigma_a$ as a function of neutron energy, where σ_a is the absorption cross sec-

tion of the specific nuclide. The term relative critical mass applies to a very large reactor for neutrons of a specific energy; since the blanket regions of an RTR are constantly "fed" neutrons from the seed regions, a blanket region simulates a large reactor neutronically. As seen in Figure 2, the critical mass of U-233 and of U-235 are about the same (i.e., relative value of 100 percent) but is only about 70 percent with Pu-239 and about 50 percent with Pu-241. This behavior is due to the high fission cross sections of the plutonium isotopes, and indicates the RTR blanket might generate more power on the uranium cycle than on the thorium cycle, even though the fuel conversion ratio is lower with uranium. In the longer term, the plutonium will generally "burn out," and the conversion ratio will become more dominant, but in the RTR, a substantial number of neutrons are fed from the seed to the blanket, tending to keep the plutonium production and the blanket power high.

The neutron absorption cross section of the fertile material has a marked influence on the required critical concentration of fissile material. Also, fissions in fertile material have a small effect. Figure 3 gives the capture cross-sections and the relative excess neutron productions for Th-232 and U-238 as a function of neutron energy. The latter is given on the right-hand part of the figure, and is proportional to ε-1 (where ε is the "fast effect"), defined as the number of fast neutrons from high-energy fissions to the number of fast neutrons from thermal-energy fissions. As indicated, ε-1 is about a factor of 4–5 higher in uranium than in thorium; however, the overall effect is small, with the fast effect being about 1.01 in PWR-uranium reactors, and about 1.0022 in PWR-thorium reactors.

As also shown in Figure 3, the thermal neutron capture cross section of thorium is significantly higher than that of U-238, while the cross sections at resonance energies are generally lower for thorium. For a given concentration of fertile material in thermal reactors, the above low-energy cross section behavior tends to cause the critical mass in thorium reactors to be relatively high. The resonance behavior of the thorium and U-238 cross sections tends to make the critical mass of the uranium cycle higher, particularly if the reactor is "nuclearly homogeneous;" however, this tendency can be decreased by fuel "lumping," as indicated below.

Figure 4 shows the effective resonance absorption integral, I^a_{eff}, as a function of scattering cross section per fertile atom (the latter varies inversely with the fertile material concentration); the effect of "nuclear homogeneity" and "fuel lumping" is also indicated. The net effect of the above generally causes a thermal reactor utilizing the thorium cycle and using lumped fuel, to operate with a higher fuel enrichment and a lower fertile concentration than does the corresponding reactor using the uranium cycle. However, if the fuel is distrib-

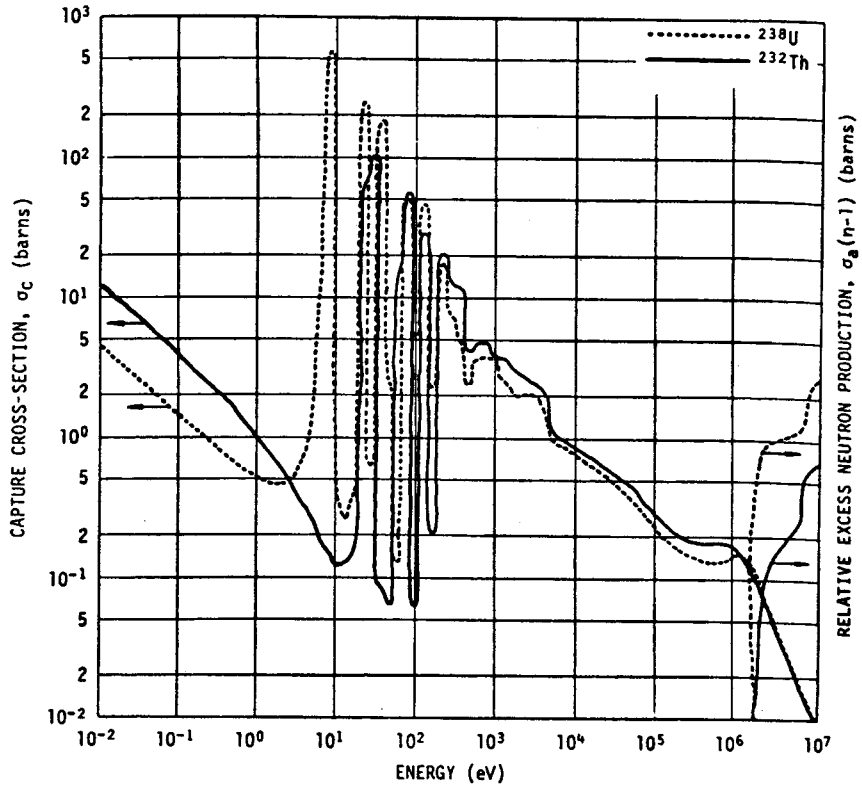

Figure 3: Capture cross-sections and relative excess neutron productions for Th-232 and U-238 as a function of neutron energy.[11]

uted homogeneously (in a nuclear sense) in the moderator rather than being lumped, the resonance absorptions in fertile material have an increased influence on critical mass such that the thorium cycle may require a lower enrichment than does the uranium cycle. The above implies that RTR and PWR reactors should tend to prefer the uranium cycle, and HTGRs the thorium cycle. This follows since in light-water-moderatored reactors the fertile material loading is relatively high to keep neutron absorptions in water at a low level; also, it is economically attractive to keep fissile concentrations low, which implies the uranium cycle with fuel lumping, as used in PWRs. In

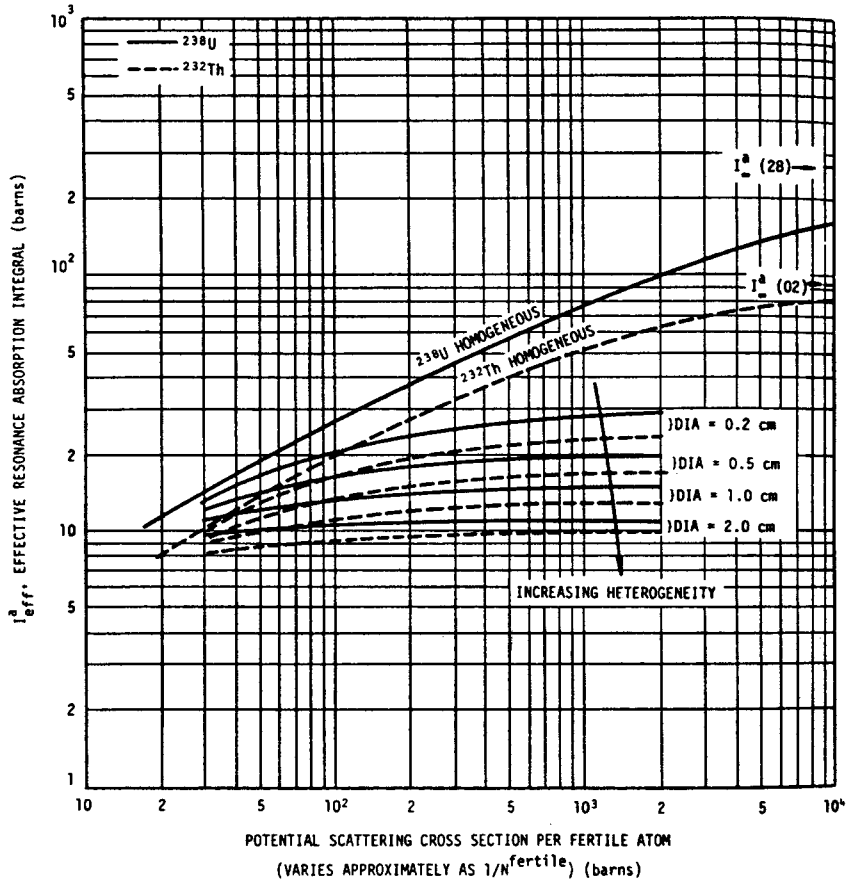

Figure 4: Variation of the effective resonance absorption integral, I^a_{eff}, for Th-232 and U-238 as a function of fertile concentration and heterogeneity (based on metal at 27°C).

HTGRs, the moderator/coolant is graphite/helium which has a low absorption cross section. As a result, the fertile material concentration can be relatively low so the fuel critical mass is not excessive. Further, the fuel is relatively "homogeneously mixed," which tends to make neutron resonance absorptions relatively high in uranium cycles. Both of the above tend to favor use of the thorium cycle for economic reasons. With once-through fuel cycles, however, there is still a small economic advantage to use of the uranium cycle in HTGRs because less "fuel value" is discarded at the end of the cycle.

The proliferation resistance of the plutonium produced in HTGRs is very similar on either the thorium or the uranium fuel cycle, and comparable with that produced in the RTR. This is a result of the nuclear characteristics of the HTGR, which is moderated with graphite and cooled with helium, with fuel rods consisting of a mixture of coated microspheres in a carbon matrix. The microspheres containing fertile material are thorium oxide in the thorium cycle and natural uranium oxide in the uranium cycle. In both cycles the fissile-fuel microspheres contain low-enriched uranium. The proliferation resistance of the plutonium produced in spent fuel is directly influenced by the burnup of the "fertile" and the "fissile" fuels. In an HTGR, both the fertile and fissile fuels are exposed to high burnups, even though both fertile and the fissile fuels remain in the reactor for the same time (~3 years). In PWRs, however, the nuclear characteristics are such that exposing both the fertile and fissile fuels for the same time results in relatively low fertile material burnup. The RTR overcomes that feature by operating with a seed-blanket arrangement, such that the fertile fuel is in the reactor about 3 times as long as the fissile fuel. As a result, both the RTR and the HTGR tend to have similar values for the fertile and the fissile fuel burnups, and similar degrees of proliferation resistance for the plutonium in the spent fuel. Since the proliferation resistance of the plutonium in the spent fuel from HTGRs is similar for uranium and for thorium once-through fuel cycles, the same may be true for the RTR uranium and thorium once-through cycles. On the uranium cycle, the RTR would retain its seed-blanket features, with slightly-enriched uranium distributing a natural uranium blanket.

In an HTGR, the effective σ_a of the fertile material increases when changing from the thorium to the uranium cycle. This in itself would tend to increase the presence of "free" U-235 in natural uranium results in lower fuel c on the uranium once-through cycle. In an RTR, the effective σ_a of the fertile material remains about the same when changing from the thorium to the uranium cycle. Because of this, the RTR probably tends to economically prefer the uranium cycle more than the HTGR on once-through cycles. The proliferation resistance of the plutonium in spent RTR fuel would probably be high on either the uranium or the thorium cycle, but somewhat higher on the thorium cycle.

As indicated above, the primary disadvantages of the thorium cycle are associated with the relatively high unit cost of fissile fuel in thermal reactors, and the lack of fissile material in the mined thorium. However, some physical property advantages are associated with the use of thorium.[12] Thorium cycles are generally more dependent than uranium upon a technology that permits

fuels to be fabricated, moved, and recycled inexpensively. Other differences in the two cycles are:[13] the absorption cross section of fission products in the thorium cycle are slightly lower than in the uranium cycle; the delayed-neutron fraction associated with fission of U-233 is ~0.0027, ~0.0065 for U-235, ~0.0021 for Pu-239, and ~0.0049 for Pu-241; the available energy release per fission is ~192 MeV/fission from U-233, ~195 MeV/fission from U-235, and ~202 MeV/fission from Pu-239.

While natural thorium is more abundant than uranium in the very long term, most of the thorium reserves are present as very low grade ores;[14] the amounts of low-cost reserves are about the same for uranium and thorium. In any event, the cost of fertile material per se is not economically significant for either the thorium or the uranium cycle for long times; much more important is the cost associated with recovering fissile fuel from the uranium ores.

RADKOWSKY THORIUM REACTOR (RTR) CONCEPT

The RTR concept consists of a seed-blanket arrangement, with use of thorium in the blanket and slightly enriched uranium in the seed; it is described in reference 1. This section summarizes features pertinent to the review performed. A key feature of the design is use of a heterogeneous, seed-blanket-unit (SBU) fuel assembly, with the thorium blanket part of the fuel assembly separate from the uranium-seed part. The separation allows independent fuel management of the thorium blanket and the "driving" part of the core consisting of the "seed." The intent is to have high "in situ" fissioning of the U-233 bred in the blanket, with the seed suppling neutrons to the blanket.

The SBU geometry provides the necessary flexibility to be compatible with existing pressurized water reactor power plants. The RTR fuel can replace a standard uranium fuel assembly in conventional PWRs or VVERs (Russian PWR). Emphasis in the design presented was on VVER application, termed the VVERT. A 1,000 MWe reactor was treated. In addition, the heterogeneity of the core design allows separate optimization of the seed and blanket lattices. At the same time, the increased flexibility results in more fuel shuffling during refueling outages, and more complicated quality-assurance records. While the RTR concept could be incorporated into operating PWRs, such a changeover would involve additional costs, such as that associated with replacement of the PWR fuel "basket" and control-rod systems with corresponding RTR systems. Also, changeover during a PWR lifetime would require discard of valuable fuel, unless the partly-burned fuel could be transported to another similar PWR and used there. It is more likely that the RTR would be utilized in a new reactor rather than in converting a PWR.

The average power density in the VVERT was 106 kW/liter, which is higher than in a PWR of the vintage having one-year refueling (1/3 of the core replaced per year) and a fuel burnup of ~34 MWd/kg heavy metal. The latter values were apparently used in the comparison that Radkowsky *et al.* performed, and were also used here for consistency. PWRs of such vintage had a core power density of ~90–95 kW/liter. For equitable comparison purposes, the power density of the PWR evaluated here was increased to 106 kW/liter. It is noted that present PWRs operate at core power densities up to ~105 kw/liter, with refueling periods of 18–24 months, and fuel exposures in the 40–50 MWd/kg range. In order to achieve the above, the fuel enrichment of the initial and makeup fuel is relatively high, increasing the fuel cycle costs. However, the total power costs are reduced by such operation. This review did not evaluate overall power costs. The PWR evaluated is believed to give a fair comparison of fuel cycle costs in PWRs and RTRs.

The seed fuel consisted of U/Zr-alloy rods, which was claimed to be consistent with the fuel technology capabilities of the fuel vendor industry of the Russian Federation. However, no specific data was provided. The size of rods and of associated unit cells were determined by considering neutronic and heat removal aspects. The blanket V_m/V_f (moderator-to-fuel volume ratio) was chosen based on optimizing U-233 buildup and to obtain efficient fissioning, and resulted in a blanket unit cell similar to that for a conventional PWR (V_m/V_f of 1.9 vs. 2.0 for PWR). The seed region had a V_m/V_f value of 3.1; the relatively high value was to reduce the epithermal neutron absorptions in U-238 and consequently reduce the buildup of plutonium isotopes.

The RTR blanket fuel consists of thorium with addition of slightly-enriched UO_2. The uranium is added to generate power in the blanket and to "denature" the U-233 bred within the blanket. For reasons of fuel economy, the blanket in-core residence time is quite long (about 10 years with a burnup of ~100 MWd/kg). The seed part of an SBU is replaced on an annual basis, with a three-year cycle.

A novel fuel in-core management scheme is employed. The standard multi-batch fuel management of a PWR is replaced by a more complicated scheme, based on two separate fuel flow routes (i.e., seed route and blanket route). Seed fuel is treated similarly to standard PWR assemblies, with ~1/3 of seeds replaced annually by fresh seeds; the remaining 2/3rds (partially depleted) are reshuffled/relocated. Each fresh seed is loaded into an empty blanket, forming a new fuel type. These new fuel type assemblies are reshuffled together with partially depleted blanket-seed assemblies to form a reload configuration for the next cycle.

In summary, fuel management is based on a quasi 3-batch-reload scheme. One-third of all seed subassemblies are replaced annually by fresh seeds, while the remaining two thirds are left within corresponding blanket subas-

semblies and reshuffled as partially depleted fuel assemblies. The in-core residence time of seed subassemblies is 3 years. The blanket subassemblies are burned for ten years, with fresh seed reinserted every three years. The reload configuration is generated on the basis of 3 batches: fresh fuel (F), once burned fuel (O), and twice burned fuel (T). No "fresh" assemblies were loaded in peripheral positions (i.e., at reflector boundaries). Most of the peripheral positions are occupied by once-through fuel. Burnable poisons are used to compensate for local power peaking. The reactive control system of the RTR core has burnable poisons and a control rod system, without utilization of soluble-boron control during operations.

Cycle 1 has three enrichment values for fuel, to simulate effectively starting out with an "equilibrium" core. Because initially there are no fission products in the reactor, the initial loading of fissile fuel is lower than subsequent cycle loadings. The blanket contains 1,595 kg of uranium of 12 percent enrichment, and the seed contains 5,305 kg of uranium, with 2,894 kg being of ~20 percent enrichment and 2,411 kg being of 17 percent enrichment. Approximately one third of the seed fuel is replaced after one year; under equilibrium refueling, 1/3 of the seed fuel is replaced each year. After 10 years, the blanket is replaced with one having the initial blanket composition. Only a third of the seed fuel in the SBU, however, is replaced as a unit at the time of blanket replacement.

The seed fuel consists of uranium zirconium alloy clad with zirconium alloy. From the fuel loading, the power fraction generated in the seed, and the volume of the seed region, the average exposure of the seed fuel during a cycle is over 150,000 MWd/kg (peak values could be much higher). The percent of power generated in the blanket is 41.9 percent, with 58.1 percent generated in the seed. The average relative power density of the blanket is 71.0 percent, while that of the core is 141.7 percent.

No reactor analysis calculations were performed in this review, with the Radkowsky *et al.* results being utilized. Since the interplay of reactor physics, power distributions, heat-transfer and fluid-flow distributions, fuel shuffling, and economics are very involved and very important in determining reactor performance, it would be prudent if an experienced PWR vendor perform such calculations for the RTR to verify the results given.

For both the RTR and PWR, the on-site spent-fuel storage volume is considered to be that required for 10 years of storage plus one reactor core volume. The reference on-site storage costs were taken to be the equivalent of 0.3 mill/kwhe for the PWR; those for the RTR were lower to account for the smaller volume of stored fuel, and the lower level of decay heat and radioactivity associated with the RTR fuel.

A Multi-Purpose Container (MPC)[15,16,17] was assumed to be used to transport spent fuel from the reactor site to a storage/disposal facility at an overall cost of $2.82 million/MPC. The number of MPCs required was determined by the amount of shipped fuel and the quantity shipped in an MPC.

RELATIVE PROLIFERATION RESISTANCE OF THE RTR AND COMPARISON WITH PWR

Radkowsky *et al.*[18] performed a relatively extensive analysis of the proliferation resistance of the RTR fuel cycle, considering the amount and composition of the plutonium (and U-233) in the spent fuel; also, the proliferation resistance of the RTR fuel cycle was measured by the critical mass of a weapon from the spent fuel, the degradation in weapon yield due to premature ignition, the degradation in weapon use because of high internal heat generation in the weapons material, and the probability of a "nominal" and of a "fizzle" yield. The values below are from reference 1.

The critical weapon mass of plutonium was given as 5.9 kg for RTR seed material, 6.5 kg for RTR blanket material, 5.5 kg for PWR grade plutonium, and 4.3 kg for weapon grade plutonium.

The rate of plutonium production for a 1,000 MWe RTR was 36.6 kg/y from the RTR seed plus 11.8 kg/y from the RTR blanket. This compares with ~250 kg/y from a PWR.

The spontaneous neutron source relative to a value of unity for weapon-grade plutonium, was 7 for PWR plutonium,13 for RTR seed plutonium, and 22 for RTR blanket plutonium.

Compared to a relative value of unity for weapons-grade plutonium, the decay heat generated in RTR seed plutonium was 24.2, 47.5 in RTR blanket plutonium, and 8.8 in PWR plutonium.

The compositions of the plutonium produced in the RTR and the PWR are given in Table 1.

The probability of a "nominal" yield and a "fissile" yield from various grades of plutonium are given in Table 2. The results indicate that while PWR plutonium is not likely to produce an "acceptable" weapon, the probability is substantially lower with RTR plutonium. In general, the above information does not appear unreasonable.

Overall, the distinguishing characteristics of the proliferation resistance provided by the RTR relative to conventional PWRs considered in this review are: (1) a reduction in the amount of plutonium present in the spent fuel, and (2) a deterioration in the weapons capability of that plutonium. The RTR

Table 1: Plutonium production rates and associated plutonium compositions for the RTR and a PWR (weapon grade composition given for comparison).

Plutonium isotope	*RTR (Th/U) seed & blanket* Fraction of isotope in plutonium	*PWR (U)* Fraction of isotope in plutonium	*Weapon grade (for comparison)* Fraction of isotope in plutonium
Pu-238	0.0784	0.010	0.00012
Pu-239	0.4445	0.590	0.938
Pu-240	0.2067	0.210	0.058
Pu-241	0.1530	0.140	0.0035
Pu-242	0.1171	0.050	0.00022
Total fraction	1.00	1.00	1.00
Total plutonium production rate (kg/GWe-yr)	48.4	~250	-
Sum of Pu-239 and Pu-241 fractions	0.598	0.730	0.942

spent fuel contains ~20 percent of the amount of plutonium in PWR spent fuel. Also, the plutonium from an RTR has much higher levels of Pu-238, Pu-240, and Pu-242, and much lower levels of Pu-249 and Pu-241. Also, the U-233 produced in the blanket thorium is "denatured" by the slightly enriched uranium added to the blanket for that purpose as well as to increase the blanket power level. The blanket uranium also contains gamma-emitting daughters of U-232, which in itself makes weapons fabrication difficult. Overall, the potential weapons material produced in an RTR is difficult to handle and fabricate into weapons because of the Pu-238 and U-232, and has a significantly lower explosive "yield" because of neutrons from the spontaneous fission of Pu-240 and Pu-242.

It should be noted that PWRs operating on the once-through uranium cycle are generally considered to provide adequate proliferation resistance. Further, the PWR in this review employed yearly refueling with a 3-year reactor-residence time to be consistent with the RTR 3-year cycle. That stipulation corresponds to a PWR fuel burnup of ~34 MWd/kg. PWR proliferation resistance is directly related to fuel burnup and inversely related to initial fuel enrichment; changing to an 18–24 month refueling period and a fuel burnup of ~40–50 MWd/kg only slightly increases relative PWR proliferation resistance.,

Table 2: Probability of a "nominal" and a "fizzle" yield versus plutonium grade.

Yield	Weapon grade Pu	PWR grade Pu	RTR-seed grade Pu	RTR-blanket grade PU
"Nominal"	0.68	0.07	0.006	0.0002
"Fizzle"	0.06	0.36	0.55	0.74

RELATIVE FUEL CYCLE COST EVALUATION OF THE RTR AND PWR

In comparing the RTR and PWR fuel cycle costs, the values of RTR fuel loadings and enrichments were taken as those given in reference 1. Both reactors were assumed to generate 1,000 MWe, operate with one year between refueling, with all fuel replaced in three years (for the RTR the seed fuel was replaced in three years, while the blanket was replaced every 10 years). The average core power densities of the two reactors were taken to be the same to put them on equivalent bases; since the average core power density of the RTR was 106 kW/liter, the size of the PWR core was adjusted to reflect increasing the power density from 90 kW/liter to 106. This effectively reduced the PWR nominal 95 MT (metric tons) uranium loading to 81 MT. The reactors were assumed to be "on line" 300 days per year, and to operate for 30 years. The cost of natural uranium was taken to be $25/kg uranium and the cost of SWUs $100/kg; the "tails" enrichment from the diffusion plant was taken to be 0.20 percent U-235.

The RTR initial blanket loading (good for 10 years) was 36,100 kg of thorium, plus 1,600 kg of uranium of 12 percent enrichment. The initial seed fuel loading was 2,900 kg uranium of ~20 percent enrichment, plus 2,400 kg uranium of 17 percent enrichment. The annual seed makeup was ~3,600 kg uranium of ~20 percent enrichment.

For the PWR, the initial core loading consisted of 27,000 kg uranium of 1.5 percent enrichment, 27,000 kg of 2.4 percent enrichment, and 27,000 kg of 3.3 percent enrichment. The annual fuel makeup was 27,000 kg uranium of 3.3 percent enrichment.

For the RTR, the initial fuel loading required about 264 MT of mined natural ore (uranium and thorium), compared with about 349 MT of natural uranium for the PWR. Subsequent yearly fuel reloads for the RTR required mining about 140 MT of natural uranium per year over the next 9 years. The overall RTR fuel cycle was effectively repeated starting the 11th and 21st year.

For the PWR, the yearly reloads required mining about 164 MT of natural uranium per year. The Separative Work Units (SWUs) required to enrich the fuel for the initial RTR fuel loading were about 378 MT SWUs; the corresponding SWUs for a PWR were about 240 MT. For the subsequent annual fuel makeup, the RTR core required about 165 MT SWUs/year, while the corresponding value for the PWR was about 130 MT.

The fuel fabrication cost for the RTR blanket fuel was estimated to be ~$150/kg heavy metal (HM), with the corresponding value for the PWR fuel being $130/kg; the difference was to account for the presence of gaseous radioactivity associated with thorium decay products. The fuel fabrication cost for the RTR seed fuel is not known, but the cost of fabricating (by extrusion) uranium-zirconium-alloy metallic fuel rods (clad with zirconium alloy) probably would be 10–20 percent that of PWR UO_2 fuel rods. However, the average uranium loading of the seed-fuel is only about 16 percent that of a PWR fuel rod, so the seed-fuel rod cost per MT of uranium would be in the range of 0.6–1.2 that of a PWR fuel rod. A value of unity was used in this review, corresponding to $130/kg uranium.

Overall costs considered were those of: fuel fabrication; mined natural uranium: enrichment (SWUs); losses during fabrication; conversion of U_3O_8 to UF_6; conversion of UF_6 to UO_2; upgrading ThO_2 to reactor grade; on-site storage of spent fuel; and transportation of spent fuel away from reactor to storage/disposal. The unit costs of the first three items have already been given. The fabrication losses were estimated to be 0.2 percent of the amount fabricated, with half of that recovered and recycled and the other half needing replacement. The cost of converting U_3O_8 to UF_6 was taken to be $3/kg; the cost of converting UF_6 to UO_2 was estimated to be $1/kg; and the cost of converting ThO_2 to reactor grade material was taken to be $1.5/kg. The costs of on-site storage of fuel and of transporting spent fuel away from the reactor site to storage/disposal are discussed below.

The spent fuel from the reactor was stored "on-site" for 10 years. The cost of on-site PWR spent fuel storage was estimated on the basis that its effective cost corresponded to 0.3 mill/kWhe in generating cost. Also, it was estimated that the volume of spent fuel storage for the PWR was the volume of fuel that enters on-site storage over a 10-year period, plus one core loading. The result was a requirement of 4.6 core volumes of spent fuel storage to be built by the time the reactor began operation. Discounting the power cost revenues (inverse discount factor of 1.085) associated with 0.3 mill/kWhe over 30 years of reactor operation gave $\$25.2 \times 10^6$ as the cost for the PWR on-site fuel storage facility at reactor start-up.

For the RTR, there is a need for storing seed units for the first 10 years, and all the blanket units at the end of 10 years. The effective fuel enrichment of the spent seed is about 5 percent compared with ~1 percent for the PWR spent fuel; as a result, the storage volume required for the seed fuel was estimated to be twice the actual seed volume. After 10 years, the blanket volume is moved to storage, along with the fully spent core seeds (1/3 of the total seed volume). As a result, 2/3 of a core seed volume can be stored in the blanket assemblies without penalty, which effectively means that there is a need to store 8/3 of core seed volume plus a reactor core volume. Since the seed volume is 41 percent of a core volume, the above requires the storage of 1.093 core volumes (without penalty), plus 1 core volume. Applying the factor-of-two penalty for seed storage, the total RTR 10 year storage requirement is 3.19 + 1, or 4.19 core volumes. In estimating the cost reduction factor associated with the smaller storage volume for the RTR, the relative volumes were raised to the 0.6 power, giving a factor of 0.95 to be applied. In addition, a factor was applied to account for the lower decay heat load and lower radioactivity level of the RTR spent fuel.

In estimating the latter, a first order approximation was used for decay heat and decay radioactivity as given in Glasstone and Sesonske[19]; the approximation estimates that both fission-product decay heat and fission-product radioactivity are proportional to: $[(t\text{-}T_0)^{-0.2} - (t^{-0.2})]$, where $t\text{-}T_0$ is the cooling time (in days), T_0 is the reactor irradiation time (in days), and t is the cooling time plus the irradiation time (in days). The above does not take into consideration the influence of actinides, but estimates by others indicate that consideration of the fission products alone are adequate as a first approximation over 10 years of spent fuel storage. England[20] gives calculated values for the decay heat (from fission products and actinides) from PWR fuel after 3 years irradiation as a function of cooling time (up to 5.7 years), while Radkowsky[21] gives estimates for the RTR decay heat (from fission products and actinides) as well as for the RTR decay radioactivity (from fission products and actinides) for cooling times from end-of-irradiation to times much in excess of 10 years. The results show that fission products are the dominant source of heat and of radioactivity for at least 10 years of storage, although they do not indicate that decay heat and decay radioactivity are proportional to each other with increasing cooling time, or necessarily follow the Glasstone and Sesonske equation. Nonetheless, it appears adequate to use the Glasstone and Sesonske equation as a first approximation, and it was used here. The results obtained indicated that the decay heat and decay radioactivity of the RTR fuel in storage was about 72 percent that of the PWR fuel. The corresponding fraction was raised to the 0.4 power to estimate the associated cost

Table 3: RTR fuel cycle costs.

Year	Fuel Fab.[a]	Nat. U[b]	SWU[c]	Loss[d]	UF6[e]	Other[f]	Storage[g]	AFR[h]	Undisc.[i]	Disc. Fac.[j]	Disc. Tot.[k]
1	6.344	6.61	37.8	0.057	0.793	0.061	20.8		72.4653	1	72.4653
2	0.468	3.5	16.5	0.021	0.42	0.004			20.9125	1.085	19.2742
3	0.468	3.5	16.5	0.021	0.42	0.004			20.9125	1.1772	17.7643
4	0.468	3.5	16.5	0.021	0.42	0.004			20.9125	1.2773	16.3726
5	0.468	3.5	16.5	0.021	0.42	0.004			20.9125	1.3859	15.0899
6	0.468	3.5	16.5	0.021	0.42	0.004			20.9125	1.5037	13.9078
7	0.468	3.5	16.5	0.021	0.42	0.004			20.9125	1.6315	12.8182
8	0.468	3.5	16.5	0.021	0.42	0.004			20.9125	1.7701	11.814
9	0.468	3.5	16.5	0.021	0.42	0.004			20.9125	1.9206	10.8885
10	0.468	3.5	16.5	0.021	0.42	0.004			20.9125	2.0839	10.0355
11	6.12	5.33	20.62	0.038	0.64	0.059		2.5098	35.3169	2.261	15.6202
12	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	2.4532	9.5478
13	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	2.6617	8.79981
14	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	2.8879	8.11042
15	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	3.1334	7.47505
16	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	3.3997	6.88944
17	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	3.6887	6.34972
18	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	4.0023	5.85227
19	0.468	3.5	16.5	0.021	0.42	0.004		0	20.9125	4.3425	4.81583
20	0.468	3.5	16.5	0.021	0.42	0.004		0	20.9125	4.7116	4.43856
21	6.12	5.33	20.62	0.038	0.64	0.059		21.883	54.6903	5.112	10.6983
22	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	5.5466	4.22285
23	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	6.018	3.89203
24	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	6.5296	3.58712

24	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	6.5296	3.58712

Table 3: RTR fuel cycle costs. (continued)

Year	Fuel Fab.[a]	Nat. U[b]	SWU[c]	Loss[d]	UF6[e]	Other[f]	Storage[g]	AFR[h]	Undisc.[i]	Disc. Fac.[j]	Disc. Tot.[k]
25	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	7.0846	3.3061
26	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	7.6868	3.0471
27	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	8.3401	2.80839
28	0.468	3.5	16.5	0.021	0.42	0.004		2.5098	23.4223	9.049	2.58838
29	0.468	3.5	16.5	0.021	0.42	0.004		0	20.9125	9.8182	2.12997
30	0.468	3.5	16.5	0.021	0.42	0.004		0	20.9125	10.653	1.96311
31								21.883	21.8832	11.558	1.8933
32								2.5098	2.5098	12.541	0.20013
33								2.5098	2.5098	13.607	0.18445
34								2.5098	2.5098	14.763	0.17
35								2.5098	2.5098	16.018	0.15669
36								2.5098	2.5098	17.38	0.14441
37								2.5098	2.5098	18.857	0.1331
38								2.5098	2.5098	20.46	0.12267
39								0	0	22.199	0
40								0	0	24.086	0
41								21.883	21.8832	26.133	0.83738
Total	**31.22**	**111.77**	**524.54**	**0.699**	**13.41**	**0.277**	**20.8**	**120.87**	**823.583**		**320.415**

a. Fuel fabrication costs, undiscounted, $E6.
b. Cost of mined natural uranium, undiscounted, $E6.
c. Cost of SWUs, undiscounted, $E6.
d. Cost of fabrication losses, undiscounted, $E6.
e. Converting U308 to UF6, undiscounted, $E6.
f. Cost of other chemical conversions (UF6 to U02, upgrading Th02), undiscounted, $E6.
g. Fuel storage costs at reactor site, undiscounted, $E6.
h. Costs for shipping spent fuel from reactor site to away-from-reactor storage/disposal, undiscounted, $E6.
i. Total of all undiscounted costs (sum of items a-h), $E6.
j. Discount factor at specified year.
k. Total of all discounted costs, $E6.

Table 4: PWR fuel cycle costs.

Year	Fuel Fab.[a]	Nat. U[b]	SWU[c]	Loss[d]	UF6[e]	Other[f]	Storage[g]	AFR[h]	Undisc.[i]	Disc. Fac.[j]	Disc. Tot.20[k]
1	10.4	8.725	24	0.054	1.047	0.08	25.2		69.5055	1	69.5055
2	3.51	4.1	13	0.024	0.492	0.027			21.1531	1.085	19.496
3	3.51	4.1	13	0.024	0.492	0.027			21.1531	1.1772	17.9686
4	3.51	4.1	13	0.024	0.492	0.027			21.1531	1.2773	16.5609
5	3.51	4.1	13	0.024	0.492	0.027			21.1531	1.3859	15.2635
6	3.51	4.1	13	0.024	0.492	0.027			21.1531	1.5037	14.0678
7	3.51	4.1	13	0.024	0.492	0.027			21.1531	1.6315	12.9657
8	3.51	4.1	13	0.024	0.492	0.027			21.1531	1.7701	11.95
9	3.51	4.1	13	0.024	0.492	0.027			21.1531	1.9206	11.0138
10	3.51	4.1	13	0.024	0.492	0.027			21.1531	2.0839	10.151
11	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	2.261	12.5861
12	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	2.4532	11.6001
13	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	2.6617	10.6913
14	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	2.8879	9.85374
15	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	3.1334	9.08179
16	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	3.3997	8.37032
17	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	3.6887	7.71458
18	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	4.0023	7.11021
19	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	4.3425	6.55319
20	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	4.7116	6.0398
21	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	5.112	5.56664
22	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	5.5466	5.13054
23	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	6.018	4.72861
24	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	6.5296	4.35817

24	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	6.5296	4.35817

Table 4: PWR fuel cycle costs. (continued)

Year	Fuel Fab.[a]	Nat. U[b]	SWU[c]	Loss[d]	UF6[e]	Other[f]	Storage[g]	AFR[h]	Undisc.[i]	Disc. Fac.[j]	Disc. Tot.20[k]
25	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	7.0846	4.01674
26	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	7.6868	3.70207
27	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	8.3401	3.41204
28	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	9.049	3.14474
29	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	9.8182	2.89838
30	3.51	4.1	13	0.024	0.492	0.027		7.3038	28.4569	10.653	2.67132
31								7.3038	7.3038	11.558	0.63191
32								7.3038	7.3038	12.541	0.58241
33								7.3038	7.3038	13.607	0.53678
34								7.3038	7.3038	14.763	0.49473
35								7.3038	7.3038	16.018	0.45597
36								7.3038	7.3038	17.38	0.42025
37								7.3038	7.3038	18.857	0.38733
38								7.3038	7.3038	20.46	0.35698
39								7.3038	7.3038	22.199	0.32902
40								7.3038	7.3038	24.086	0.30324
41								21.883	21.8832	26.133	0.83738
Total	**112.19**	**127.625**	**401**	**0.753**	**15.31**	**0.863**	**25.2**	**241**	**923.943**		**333.509**

a. Fuel fabrication costs, undiscounted, $E6.
b. Cost of mined natural uranium, undiscounted, $E6.
c. Cost of SWUs, undiscounted, $E6.
d. Cost of fabrication losses, undiscounted, $E6.
e. Converting U308 to UF6, undiscounted, $E6.
f. Cost of other chemical conversions (UF6 to U02, upgrading Th02), undiscounted, $E6.
g. Fuel storage costs at reactor site, undiscounted, $E6.
h. Costs for shipping spent fuel from reactor site to away-from-reactor storage/disposal, undiscounted, $E6.
i. Total of all undiscounted costs (sum of items a-h), $E6.
j. Discount factor at specified year.
k. Total of all discounted costs, $E6.

factor to apply in estimating RTR spent fuel storage costs. That factor was 0.88. As a result, the RTR spent fuel storage costs were estimated to be $\$25.2 \times 0.95 \times 0.88$ million, or $\$20.8 \times 10^6$.

In estimating costs for transporting spent fuel away from the reactor site to storage/disposal, it was assumed that a Multi-Purpose Container (MPC)[22,23] was employed to transport the 10-year-old spent fuel. The cost of the using the container was taken to be $2.82 million, including handling, transportation, and disposal cost. The MPC held 21 PWR fuel assemblies, or 21 RTR Seed Blanket Units; it would nominally hold 51 seed fuel assemblies, but that was reduced to 25 because of criticality concerns (the spent RTR fuel had an effective enrichment of about 5 percent, versus about 1 percent for spent PWR fuel). Combined with a blanket assembly, no penalty was assigned to seed assemblies. On the above bases, the number of MPCs required as a function of time were estimated, until all spent fuel was shipped during the 41st year after reactor start-up. The associated costs were discounted to give the effective cost of shipping spent fuel from the reactor site to the away-from-reactor storage/disposal. The number of shipping/storage containers required for the RTR fuel was relatively-low, and gave a significant advantage to the RTR in that cost category. (It should be noted there is much uncertainty concerning what costs will be covered by the 1 mill/kwhe that US nuclear utilities presently pay to the US Department of Energy for providing long-term storage/disposal of spent fuel. Some interpretations have been that the payment includes transporting spent fuel from the reactor site. The comparison made here under "reference" conditions appears "fair" for a "one-on-one" comparison; nonetheless, including spent fuel transportation/storage/disposal costs at this time might be considered controversial.)

Based on the above, a reactor life of 30 years, and a cash flow analysis to account for the time value of costs/income, the sums of fuel costs over 41 years (to include fuel shipping the year following ten-year storage) were estimated for the RTR and PWR. The separate items of fuel costs and the total discounted fuel cycle costs are given in Table 3 for the RTR and in Table 4 for the PWR. The inverse cost discount factor was 1.085, which included 6 percent for the cost of money, and the remaining 2.5 percent covered costs incurred before reactor start-up, insurance, licenses, profit, etc. The discounted power revenues were $\$839.5 \times 10^6$. Overall, for the reference evaluation conditions, the total fuel cycle costs of the RTR were about 4 percent lower than for the PWR. Unit fuel cycle costs were 3.82 mills/kWhe for the RTR, and 3.97 mills/kWhe for the PWR. Not including charges for the spent fuel transportation away from the reactor for storage/disposal would have resulted in the RTR fuel cycle costs being 3 percent higher than the PWR costs. The fuel cycle costs for the

RTR and for the PWR were calculated on what are reasonable unit cost bases. At the same time, there are significant uncertainties associated with a number of the parameters. The difference in the estimated fuel cycle costs for the RTR and PWR is much smaller than the uncertainty in the actual fuel cycle costs.

COMMENTS ON USE OF URANIUM CYCLE IN RTR

Emphasis is given to the use of thorium in the RTR, since the η value of U-233 is relatively high, and so the thorium cycle gives a higher fissile-fuel conversion ratio than the uranium cycle. However, as pointed out in the third section, the critical mass associated with Pu-239 and Pu-241 and the uranium cycle is relatively low. Since a substantial fraction of neutrons absorbed in the blanket region originate in the seed region, and the fission cross section of plutonium is relatively high, the equilibrium power in the blanket may be high even though the fuel conversion ratio is low. In effect, the higher conversion ratio of the thorium cycle may be more than compensated by the lower critical mass of the uranium cycle under conditions of substantial neutron leakage from the fuel seed region into the blanket region. As a result, the uranium cycle may have an economic advantage over the thorium cycle, particularly since the use of uranium brings with it some "free" U-235. If necessary, additional "burnable poison" could be added to increase the "reactivity lifetime." The uranium cycle probably would give proliferation resistance similar to that of the RTR, since both the blanket and seed fuel would again be exposed to high fuel burnup.

While comparisons of the thorium and uranium cycles in an RTR are not available, a comparison of those cycles in a High Temperature Gas-Cooled Reactor (HTGR) appears useful since both reactor types result in similar fissile and fertile fuel exposures. This along with fuel-cycle economic features are discussed more fully under the section on Thorium and Uranium Fuel Cycles. The HTGR tends to economically prefer use of the thorium cycle under fuel recycle conditions, but prefers the uranium cycle for "once-through" type fueling. In both cycles, fuel is exposed to high exposures (~100 MWd/kg). Once-through fueling was considered in the cases given below. It is probable that the relative results for the two fuel cycles are meaningful to the RTR.

Table 5 gives, on comparable bases, the estimated plutonium production rates and associated plutonium compositions in the spent fuel from the above two HTGR cycles,[24] along with results from the RTR (and also the PWR for comparison). As shown, the spent fuels from the HTGRs and the RTR appear to contain plutonium having comparable proliferation resistances, with the RTR probably having some advantage. In the HTGR studies, it was found that

the plutonium was more effective in maintaining a low critical mass than had been initially anticipated. Specifically, the amount of burnable poisons added to the reactor cores for the two cycles were estimated on the basis of attaining an average fuel burnup of ~100 MWd/kg. As it turned out, the fuel exposure with use of the thorium cycle was about 85 MWd/kg, while it was ~115 MWd/kg with the uranium cycle; this implies that the bred U-233 in the thorium cycle was less effective than expected in maintaining criticality, while the bred plutonium in the uranium cycle was more effective than originally expected. The same may apply to the RTR.

SAFETY/TECHNOLOGY/ECONOMIC CONCERNS

There are three identified areas of concern involving safety/technology/economics; one is the practicality of the long fuel exposures of the blanket rods, another the use of zirconium-uranium alloy clad in zirconium alloy for the seed fuel, and thirdly, the ability to extensively shuffle fuel and replace spent seed from a seed-blanket unit without impacting plant availability. These are addressed below.

The RTR blanket fuel consists of ThO_2/UO_2 rods clad with zirconium alloy that are exposed to very long times (~10 years) and high burnup (~100 MWd/kg) in a high-temperature water environment containing small amounts of hydrogen. Meeting these conditions does not appear to be practical because of corrosion and hydriding of the cladding. The problem is with the cladding alloy and water and not the fuel. The fuel-clad interaction itself has been successfully addressed in test reactor studies, in which fuel and clad were exposed to high burnup over relatively short periods of time. A.R.Olsen *et al.*[25] reported that thoria urania fuel performed well at burnups up to ~80 MWd/kg HM, without evidence of significant problems. However, tests of fuel rods in a light water environment are not as encouraging, with satisfactory performance only demonstrated up to ~ 5-6 years exposure with fuel burnups of 50–60 MWd/kg. Cladding interactions occur with high-temperature water containing small quantities of hydrogen from the radiolysis of water, hydrogen added to suppress the oxygen levels, and from the reaction of water with zirconium. After exposure times of ~6 years, corrosion and hydriding tend to cause cladding failures. While work on zirconium-niobium alloys appears promising, such alloys might require so much niobium for 10-year exposures that the neutron absorption cross section of the cladding is excessive. Development of an improved alloy appears necessary for RTR application, and significant research, development and testing appears necessary.

Table 5: Plutonium production rates and associated plutonium compositions from a thorium cycle HTGR, a uranium cycle HTGR, and the thorium cycle RTR (for comparison, the PWR on the uranium cycle is included).

Plutonium isotope	RTR(Th) seed & blanket Fraction of isotope in plutonium	HTGR(Th) Fraction of isotope in plutonium	HTGR(U) Fraction of isotope in plutonium	PWR(U) (for comparison) Fraction of isotope in plutonium
Pu-238	0.0784	0.0605	0.0521	0.010
Pu-239	0.4445	0.4686	0.4386	0.590
Pu-240	0.2067	0.2217	0.2318	0.210
Pu-241	0.1530	0.1716	0.1792	0.140
Pu-242	0.1171	0.0776	0.0983	0.050
Total fraction	1.00	1.0000	1.0000	1.00
Total plutonium production rate, kg/GWe-yr	48.4	65.2	72.3	~250
Sum of Pu-239 and Pu-241 fractions	0.598	0.6402	0.6178	0.730

The RTR seed fuel consists of a metallic alloy of uranium and zirconium clad in zirconium alloy. This fuel reaches a peak fuel burnup in excess of 150 MWd/kg heavy metal over a 3 year exposure. Also, the average power density in the seed region is 40 percent higher than the average power density of a PWR. Little information is readily available on the performance of this fuel under normal or extreme accident conditions, and significant testing and development appears necessary to insure that the fuel can be exposed to RTR conditions without impacting reactor safety. Uranium undergoes phase and volume changes at relatively low temperatures, changing from the a to the b phase at 665°C, and from the b to the g phase at 775°C (where it changes from a face-centered cube to a body-centered cube with significant volume change). The above phase changes would add internal stresses inside the seed fuel. Also, it is not clear what happens to the relatively large quantity of fission gases that are generated under high burnup conditions. Further, the large amounts of zirconium present in the seed may have safety implications under severe accident conditions.

J.H.Kittel *et al.*[26] studied the effects of irradiation on uranium/thorium alloys; a number of these metal alloys were irradiated at temperatures up to 1000°C and fuel burnups of up to 10 percent Fissions per Initial Metal Atom (FIMA). Thorium itself was not exposed to significant burnup. The fuel swelling rate remained constant at about 2 percent volume increase per percent FIMA, up to about 500°C. At higher temperatures, higher swelling rates were observed, and a strong temperature sensitivity existed. At 900°C the swelling rate was about ~8 percent per percent FIMA. Specimens containing more than 25 wt percent U became warped and distorted, a condition not noted in specimens containing less than 20 wt percent U. Generally, exposing the fuel to higher burnup led to higher swelling at temperature >520°C, implying it was the burnup that led to swelling at the higher temperatures. While Zr/U alloys may exhibit a different behavior than Th/U alloys, thorium metal is well behaved and the results may be pertinent.

The data available on Zr/U alloys is very limited, and generally for conditions that exist in sodium-cooled fast breeder reactors (FBRs). Walters[27] reported that zirconium added to U-Pu fuel would yield a ternary fuel with an adequately high solidus temperature and good compatibility with stainless steel clad; a six atomic percent burnup was successfully achieved. However, FBRs operate with a sodium bond between the metal fuel and the clad, and the amount of zirconium in the metal fuel is relatively low.

Frost *et al.*[28] reported that in fast reactors zirconium can be present as the metal up to 10 percent, and that phase changes would induce significant stresses in the metal, particularly when transforming to the *g* phase. Also, it appears that the thermal conductivity of a fuel like ZrU alloy can change during irradiation.

Overall, it appears that significant R&D is necessary before the behavior of RTR seed fuel under normal and accident conditions will be sufficiently known, particularly the influence of fission gases and other fission products, fuel burnup, and Zr-U alloy structural effects on structural stability.

Finally, demonstration is needed that the extensive shuffling of seed-blanket units during refueling, combined with the replacement of spent seed fuel in a seed-blanket unit with fresh seed followed by reshuffling, does not negatively impact plant availability. A decrease in plant load factor would directly impact the cost of generating power.

Table 6: Comparison of RTR claims (some inferred) and the results of this review.

RTR Claims	Reviewer Conclusions
Pu produced is 20 percent that of PWR.	Agree, but PWR amount is acceptable.[a]
Isotopic composition of Pu produced is of substantially poorer quality than from PWR.	Agree, but PWR composition is acceptable.[a]
High Pu-238 content and U-232 presence in fuel complicates weapons fabrication.	Agree, but PWR operating on once-through uranium cycle is acceptable.[a]
RTR concept can be applied quickly to existing PWRs.	Substantial research and development/demonstration is required before it is known if it can be applied safely and economically.
Reductions in spent fuel from RTR relative to PWR reduce site-storage costs and shipping/disposal costs.	Agree, but the reductions are less than given in the RTR article because of criticality concerns with the spent fuel, and because most of the cost reductions occur many years after reactor start-up.
RTR has a fuel cycle cost about 20 percent lower than for the PWR.	RTR fuel cycle cost was estimated to be 4 percent lower than for the PWR under reference conditions.
Thorium cycle is important to the success of the RTR concept.	Uranium cycle appears to be preferable because of lower fuel cycle costs while retaining the desirable non-proliferation features.
Blanket fuel can be successfully exposed to RTR conditions.	Exposure of blanket fuel for 10 years to high-temperature water conditions containing small amounts of hydrogen is not assured. The problem is with the cladding alloy and water and not the fuel.

Table 6: Comparison of RTR claims (some inferred) and the results of this review. (continued)

RTR Claims	Reviewer Conclusions
Seed fuel can be successfully exposed to RTR conditions.	Zirconium-uranium alloy undergoes phase changes at relatively low temperatures, and the behavior of fission gases under high burnup conditions is not well known. R&D is required before fuel behavior under normal and accident conditions will be known.
Extensive fuel shuffling in RTR is not a problem with regard to plant availability.	The extensive reshuffling of all fuel during refueling, with the seed fuel independent of the blanket fuel to accommodate fresh seed loads, will need to be successfully demonstrated before its effect on plant availability will be known.

a. A nominal ~40–50 MWd/kg would only slightly increase the PWR proliferation resistance.

CONCLUSIONS

Overall, it appears that the RTR has desirable non-proliferation features, and provides a novel way to achieve high fertile material burnup in LWRs. A summary of the RTR claims and the conclusions of this review are given in Table 6.

SUMMARY

A review has been presented of a novel reactor-design concept termed the Radkowsky Thorium Reactor (RTR). The concept has potential for application in pressurized water reactors (PWR is US version; VVER is Russian version); the article reviewed emphasizes the VVER-Thorium (VVERT) reactor. A key feature is the use of a modular seed-blanket arrangement. The general reactor design features are similar to conventional PWRs such that application of the seed-blanket arrangement could be implemented rather quickly if no reactor safety, technical, or economic problems exist.

Distinguishing characteristics of the proliferation resistance provided by the RTR relative to conventional PWRs are: (1) a reduction in the amount of plutonium present in the spent fuel, and (2) a deterioration in the weapons capability of that plutonium. The RTR spent fuel contains ~20 percent of the amount of plutonium in PWR spent fuel. Also, the plutonium from an RTR has much higher levels of Pu-238, Pu-240, and Pu-242, and much lower levels of

Pu-239 and Pu-241. At the same time, PWRs operating on the once-through uranium cycle are generally considered to provide adequate proliferation resistance. Increasing the PWR fuel exposure to ~40–50 MWd/kg by going to an 18–24 month refueling period would only slightly increase the proliferation resistance of the PWR spent plutonium.

A comparison was made of the RTR and PWR fuel cycle costs on equitable bases, using a discounted cash flow analysis, with an inverse discount factor of 1.085. The cost of natural uranium was taken to be $25/kg uranium, and the cost of Separative Work Units (SWUs) $100/kg. Specific cost items treated were: fabrication, natural uranium and thorium mining, SWUs, fuel fabrication losses, chemical conversions, storage of fuel at the reactor site, and transporting fuel from the reactor to an away-from-reactor storage/disposal location. Spent fuel from the reactor was stored "on-site" for 10 years, after which it was shipped to an "away-from-reactor" storage/disposal facility. A summary of comparative discounted costs and revenues are given in Table 7. Overall, for the reference conditions, the total fuel cycle cost of the RTR was about 4 percent lower than for the PWR.

Emphasis is given to the use of thorium rather than uranium in the RTR blanket because of the higher fissile-fuel conversion ratio and the proliferation resistance of the plutonium produced. However, the critical mass of plutonium associated with the uranium cycle is relatively low. As a result, and since a substantial fraction of neutrons absorbed in the blanket region originate in the seed region, the equilibrium power in the blanket may be high even though the fuel conversion ratio is low. Overall, the uranium cycle may have an economic advantage over the thorium cycle, particularly since the use of uranium brings with it some "free" U-235. The uranium cycle might give proliferation resistance similar to that of the RTR, since both the blanket and seed fuel would again be exposed to high fuel burnup. However, the proliferation resistance of the plutonium in the spent fuel from the uranium cycle would probably be slightly less than from the thorium cycle.

While comparisons of the thorium and uranium cycles in an RTR are not available, a comparison of those cycles in a High Temperature Gas-Cooled Reactor (HTGR) appears useful. The HTGR tends to economically prefer use of the thorium cycle under fuel recycle conditions, but prefers the uranium cycle for "once-through" type fueling. In both cycles, fuel is exposed to high exposures (~100 MWd/kg), and appears to contain plutonium with high proliferation resistance in both fuel cycles (comparable with that from the RTR). In the HTGR calculations it was found that plutonium in the uranium cycle was more effective than had been initially anticipated in maintaining a low critical mass. The same may be true for the RTR on the uranium cycle.

The practicality of the RTR requires exposing zirconium-alloy clad fertile fuel rods to very long times (~10 years) and high burnup (~100 MWd/kg) in a high-temperature water environment containing small amounts of hydrogen.

Table 7: Discounted fuel cycle costs/revenues for RTR and PWR (time starts at reactor start-up and ends with shipment of the last fuel away from the reactor site).

		RTR	PWR
Fabrication costs	$\$ \times 10^6$	14.9	47.8
Natural U/Th costs	$\$ \times 10^6$	45.1	52.4
SWU costs	$\$ \times 10^6$	216.3	162.6
Chemical conversion costs and fuel fabrication losses	$\$ \times 10^6$	5.8	7.0
Reactor-site fuel storage	$\$ \times 10^6$	20.8	25.2
Away-from-reactor shipping/storage/disposal[a]	$\$ \times 10^6$	17.4	38.5
Total fuel cycle costs	**$\$ \times 10^6$**	**320.4**	**333.5**
Power revenues	$\$ \times 10^6$	839.5	839.5
Fuel cycle costs	mills/kwhe	3.82	3.97
Relative fuel cycle costs		**0.96**	**1.00**

a. If the "away-from-reactor" costs were not included, the RTR fuel cycle costs would be 3 percent higher than for the PWR.

This does not appear to be practical because of corrosion and hydriding of the cladding; additional cladding research and development/demonstration appears needed to achieve the desired conditions. Also, the very high burnup of the seed metal fuel and the high power density in the seed fuel may negatively impact reactor safety, and additional R&D appears necessary to assure acceptable seed-fuel performance. Finally, demonstration is needed that the extensive shuffling of seed-blanket units during refueling combined with the replacement of spent seed fuel from a seed-blanket unit with fresh seed followed by reshuffling does not negatively impact plant availability.

Overall, it appears that the RTR has desirable non-proliferation features, and provides a novel way to achieve high fertile material burnup in PWRs. Further, for the reference evaluation conditions, the fuel cycle cost of the RTR was slightly less than for a PWR, but the difference was small compared with the uncertainty in cost parameters. By displacing the thorium with natural uranium in the RTR concept, the fuel cycle cost might be further reduced

while retaining desirable non-proliferation features. However, the practicality of the concept requires additional R&D to achieve the blanket and seed fuel performance required, and demonstration is required of the practicality of the fuel shuffling/reloading occurring during refueling.

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ABOUT THE REVIEWER

Paul R. Kasten obtained a Ph.D. in Chemical Engineering from the University of Minnesota-Minneapolis in 1950. Following that, he was a staff member of Oak Ridge National Laboratory (ORNL) until his retirement in 1988, working in reactor physics and analysis, reactor evaluations, and reactor programs. During 1963 and 1964 he was Guest Director of the Institute for Reactor Development at the Research Center-Jülich, Germany. From 1965–1970 he was Associate Director of the Molten Salt Reactor Program at ORNL and also Director pro-tem of Reactor Studies and Evaluations in 1967. From 1966–70 he was also involved in the overall evaluation of breeder and converter reactors being carried out for the U. S. Atomic Energy Commission. From 1970 until his retirement he was Director of the Gas Cooled Reactor Programs, which included the Thorium Utilization Program. During 1975–1979 he also participated in thorium-fuel-cycle evaluations under the U.S. Nonproliferation Alternative Systems Assessment Program (NASAP), which was part of the International Nonproliferation Fuel Cycle Evaluation (INFCE); and during 1977–1979 he was responsible for the Alternate Fuel Cycle Evaluation Program (AFCEP) at ORNL, which was part of the overall NASAP effort.

He was also a part-time Professor of Nuclear Engineering at the University of Tennessee-Knoxville from 1957 until his retirement in 1994. Since then he has continued as an honorary Adjunct Professor.