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A Closed ThUOX Fuel Cycle for LWRs with ADTT (ATW) Backend for the 21st Century

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Abstract

A future nuclear energy scenario with a closed, thorium-uranium-oxide (ThUOX) fuel cycle and new light water reactors (TULWRs) supported by Accelerator Transmutation of Waste (ATW) systems could provide several improvements beyond today's once-through, UO_2-fueled nuclear technology. A deployment scenario with TULWRs plus ATWs to burn the actinides produced by these LWRs and to close the back-end of the ThUOX fuel cycle was modeled to satisfy a U.S. demand that increases linearly from 80 GWe in 2020 to 200 GWe by 2100. During the first 20 years of the scenario (2000-2020), nuclear energy production in the U.S. declines from today's 100 GWe to about 80 GWe, in accordance with forecasts of the U.S. DOE's Energy Information Administration. No new nuclear systems are added during this declining nuclear energy period, and all existing LWRs are shut down by 2045. Beginning in 2020, ATWs that transmute the actinides from existing LWRs are deployed, along with TULWRs and additional ATWs with a support ratio of 1 ATW to 7 TULWRs to meet the energy demand scenario. A final mix of 174 GWe from TULWRs and 26 GWe from ATWs provides the 200 GWe demand in 2100. Compared to a once-through LWR scenario that meets the same energy demand, the TULWR/ATW concept could result in the following improvements:

- depletion of natural uranium resources would be reduced by 50 percent;
- inventories of Pu which may result in weapons proliferation will be reduced in quantity by more than 98 percent and in quality because of higher neutron emissions and 50 times the alpha-decay heating of weapons-grade plutonium;
- actinides (and possibly fission products) for final disposal in nuclear waste would be substantially reduced; and
- the cost of fuel and the fuel cycle may be 20-30% less than the once-through UO2 fuel cycle.

Introduction

As the world transitions from a rapid growth in nuclear power during the last half of the 20th Century to a changing 21st Century, we search for a nuclear fuel cycle with sustainable, economic, and environmentally sound characteristics. A fuel cycle that includes abundant thorium has been studied extensively in the past,(1) but has not been deployed nationally for several reasons. These reasons include, but are not limited to, the following:

- Uranium has been a relatively inexpensive and an abundant fuel for safe nuclear power worldwide.
- In the U.S., at least, a "once-through" conventional LWR (CLWR) fuel cycle has been employed as most economic.
- Used fuel from the CLWRs has been stored on-site in "spent-fuel" pools, and on-site storage space has not yet been exceeded.
- There are potential limitations associated with geologic disposal of waste from the once-through U-based fuel cycle that have not been demonstrated or discovered because lessons cannot be learned from experience until a repository is constructed and waste is being packaged and stored.

Although the uranium resource is abundant, it is not inexhaustible. Non-nuclear energy resources are also not unlimited, and a worldwide realization of the hidden costs of other energy sources or a global consensus to reduce greatly the emission of greenhouse gases and other pollutants could result in a resumption of rapid growth of nuclear power similar to the 1970s in the U.S. Thus, the world may once again face the issue of limitations on economical uranium resources, as well as the continuing and escalating issues of waste disposal. Another issue is beginning to take on additional meaning, especially with recent global activities in development and deployment of weapons of mass destruction. That issue is proliferation of nuclear weapons capabilities, which requires "weapons-useable" materials for use in manufacturing those weapons.

Continued worldwide studies of these issues and how to solve them have revealed that an advanced fuel cycle may have a great potential to reduce resource depletion, to reduce quantities and improve the composition of waste for disposal, and to reduce the risk of proliferation of nuclear weapons. To examine the potential impact of a national deployment of an advanced fuel cycle, we studied a system similar to one that is currently receiving heightened attention worldwide: a combined thorium-uranium-oxide (ThUOX) fuel for new LWRs (TULWRs). The Department of Energy has recently funded a joint U.S./Russia project to examine a "seed/blanket" fueling option—called Radkowsky Thorium Fuel (RTF)(2) —for existing LWRs that employs a mixed Th-U fuel in the blanket assemblies. However, the Th-U fuel in the present systems analysis was not restricted to the RTF fuel cycle, but was modeled with a "generic" ThUOX cycle. In addition, to minimize the impact on the environment, and to reduce quantities of waste and weapons materials, the front end of the ThUOX fuel cycle was combined with a back-end accelerator-driven transmutation technology (ADTT): LANL's conceptual Accelerator Transmutation of Waste (ATW) system.(3) The ATW will be used to improve the fuel cycle by reducing quantities of actinide and possibly fission-product waste for disposal and by eliminating most of the Pu inventory in the U.S. to reduce the risk of proliferation. This coupled concept of TULWRs and ATWs produces a view of the future with greatly reduced natural resource depletion and waste volume, and with a reduction in proliferation risk, in terms of both quality and quantity of plutonium stored external to the highly radioactive and controlled cores of reactors.

The TULWR/ATW fuel cycle uses less natural-U resource than the once-through CLWR because the reactors will use thorium for 70-90% of the fuel, and they recycle ^{233}U (bred from Th), so they use a smaller quantity of enriched uranium and much reduced natural uranium. The system produces less Pu because the fuel contains less U, and the Pu is of lower "quality" for proliferation because recycling of intermediate isotopes of uranium produces more ^{238}Pu and other "non-fissile" isotopes of Pu. The combined system also generates less radioactive waste for disposal because long-lived fission products (LLFP) and actinides are separated from spent fuel and transmuted to short-lived fission products in ATWs. An additional benefit is that this processing produces a stream of separated isotopes which may be in optimal chemical forms for disposal.

In the following sections of this paper, the previous statements about this combined, ThUOX-fueled TULWR and ATW system for the production of nuclear-generated electricity out to the year 2100 will be quantified, and non-proliferation attributes will be explored. We begin by describing the scenario that defines the growth in nuclear energy and the transition to TULWRs supported by ATW backend.

Basis Scenario for Transition—Today to 2100

In 1997, The Energy Information Administration of the U.S. DOE examined the outlook for nuclear power in the U.S. out to the year 2020, with a "High nuclear", a "Reference case," and a "Low nuclear" scenario.(4) The high nuclear case is characterized by extension of licenses for all existing plants by 10 years, and the reference case by some shutdowns and some reactors retiring at the end of existing licenses. The low case assumptions include the 10-year-early retirement of all existing nuclear power plants in the U.S. In view of ongoing de-regulation of electricity generation, distribution, and sales;

recent applications for 20-year license extensions; and industry attempts to purchase U.S. nuclear power plants; for this study the "high nuclear" projection of the EIA was used, although this scenario may be approximated by some early retirements combined with 20-year license extensions and improved performance and efficiency. Thus, as is shown in Figure 1, during the first 20 years (2000-2020) of the scenario included in this study, nuclear energy production in the U.S. declines from today's 100 GWe to about 80 GWe in 2020. For the period beyond the EIA study (after 2020), all existing reactors are shut down by 2045. Also, for the present analysis neither Evolutionary LWRs nor any other nuclear systems to supply either additional needed power or to make up for retired nuclear generation during the next 20 years would be deployed (realization of this assumption, which is in accordance with the EIA assessment, would have a substantial negative impact on efforts to reduce the emission of greenhouse gases). In accordance with the ATW scenario presented in Reference 3, sufficient ATWs to transmute the actinides from the existing LWRs are included in the present study. However, whereas the referenced deployment scenario includes ATWs to burn only the actinides that will be generated through 2015, this number was increased to eliminate all actinides produced by CLWRs in the present, longer-term scenario.

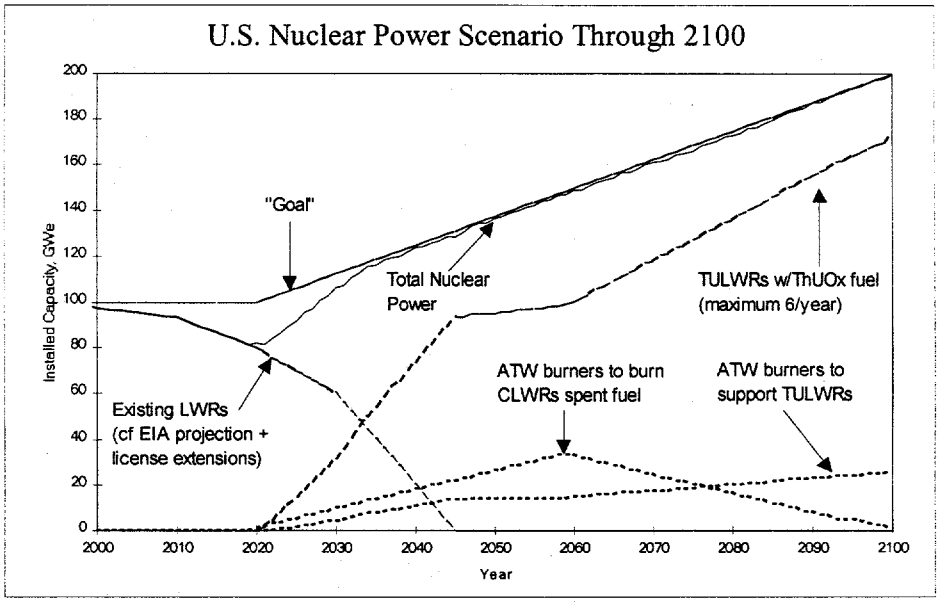

Figure 1. U.S. nuclear power scenario through the year 2100.

In a recent study at Los Alamos, a moderate-growth scenario for nuclear energy for the world (13 regions including the U.S.) was a result of an economic, energy, and environment (E^3) analysis that coupled global population estimates, productivity, and per capita energy demand to world supplies.(5) This modeling, coupled to the rest of the world, projects a growth of U.S. nuclear power to about 200 GWe in the year 2100 (this projection depends on complex interactions between many variables, including technology innovations, efficiency improvements, and carbon-taxing schemes). To supply 200 GWe by 2100, a deployment scenario was implemented that included new LWRs plus ATWs to burn the actinides produced by these LWRs. A TULWR that is fueled with 25% UO_2 and 75% ThO_2 (volume percent) would produce about 160 kg of higher actinides (mostly Pu) per year per GWe, compared to about 310 for a CLWR—this production depends strongly on reactor design (moderator to fuel ratio, refueling schedule, fuel burn-up, etc.), and may be optimized in future studies. To transmute this LWR-produced feed, an ATW will fission about 1100 kg of actinides per year per GWe, thus the support ratio is 7 GWe TULWRs per 1.05 GWe ATW. Therefore, in 2100, 174 GWe from TULWRs and 26 GWe

from ATWs provide the 200 GWe demand. Both the retirement and deployment scenarios are shown graphically in Figure 1, which includes CLWRs that retire between now and 2045, ATWs that are deployed beginning in 2020 to transmute actinides and fission products from the CLWR used fuel, TULWRs that are deployed to satisfy a growing demand for electricity, and additional ATWs that are deployed to close the back-end of the ThUOX fuel cycle.

In Figure 1 the upper solid line represents a "goal" scenario for nuclear energy. With no new reactors between today and 2020 (no "evolutionary" LWR deployment), and with planned ATW and limited TULWR deployment beginning in 2020 (dashed and light solid lines), the attainable total nuclear power is computed and is shown as the solid black line. ATWs to support the growing number of TULWRs are shown as a dashed line. The numerical model attempts to "keep up" with the growth requirement.

The resultant spent fuel production, actinide feeds for ATWs, and plutonium accumulation are determined by the growth of the four types of reactors shown on this figure.

Fuel Cycle and Inventory Analysis

The various flows of materials and places they are accumulated in today's concept for CLWRs, as a once-through, or "open" fuel cycle, are illustrated in the diagram Figure 2. This fuel cycle has a feed and spent fuel inventory that are tracked in our calculations. The thorium-uranium oxide fuel cycle with ATWs at the backend is more complex, as shown in Figure 4. The TULWR fuel cycle is similar to the CLWR cycle, but the TULWR/ATW combined fuel cycle adds an additional resource vector for thorium to the LWR Feed "F", a Separations Plant "S" (and inventory), the ATW process "A", and a second, reduced-mass waste stream. The Separations plant/inventory was not included in our systems analysis, thus the feed for ATWs was taken directly from the accumulating spent fuel from CLWRs or TULWRs.

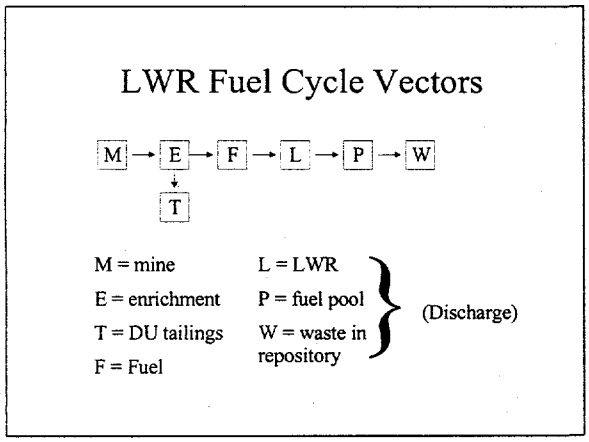

Figure 2. Fuel cycle vectors for once-through, uranium fueled CLWRs.

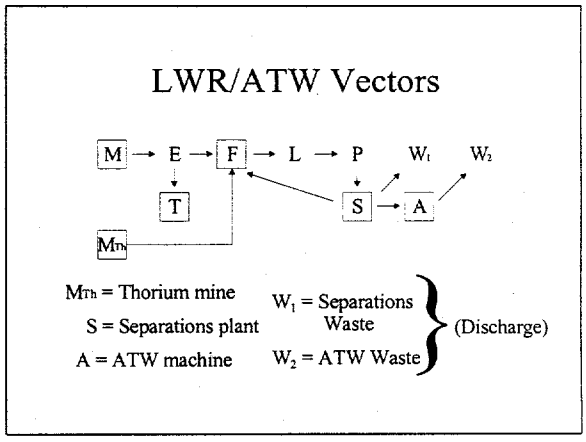

Figure 3. Fuel cycle vectors for thorium-uranium fueled TULWRs.

A depletion analysis for a "conventional" LWR was used to provide data for calculating the fuel resource requirements, spent fuel production and accumulation, actinide transmutation, and other parameters. For CLWRs, 22,460 kg/year of 5.0%-enriched U was fed to the reactors, with annual refueling and a burnup of 50,000 MWth-days/tonne heavy metal. With this feed rate and burnup and a thermal-electric conversion of 0.325, these plants would produce a nominal 1000 MWe (equivalent to 1176 GWe capacity operating at a capacity factor of 0.85). To calculate natural U mining and milling required to provide this fuel, a concentration of ^{235}U of 0.0072 in natural uranium and 0.0030 in tails was used. One-group LWR cross sections and breeding/transmutation/decay chains were used to generate actinide fission, decay, and buildup during the fuel cycle.

A similar computation was done for the ThUOX fuel cycle in the TULWRs, with the same feed, efficiency, and burnup. To compute burnup and actinide production, the SAS2 driver from SCALE(6) was used to calculate new cross sections for a PWR fuel assembly with 25% U and 75% Th (volume percents), then to run a depletion analysis with ORIGEN-S. This analysis resulted in a production of just 160 kg of higher actinides per yr vs. 310 for the CLWR. For this study, a new core fueling scheme was not designed and analyzed for various safety parameters (void reactivity coefficients, Doppler effects, etc.); however, changes in the core design can significantly change feed & discharge compositions of the Th-U fuel cycle, which may decrease ^{233}U production, increase Pu production (thus increasing total actinides), and decrease the number of TULWRs that an ATW may support. This calculation is very sensitive to spectrum-averaged cross sections, so that optimization of the reactor design, enrichment, loading, and Th:U ratio may maximize production of ^{233}U which would minimize make-up requirements for enriched uranium. Optimization could also minimize production of actinides that would require transmutation, which would allow a higher support ratio for ATWs.

A simple spreadsheet program was used to track and accumulate the production of actinides, inventories residing in CLWR and TULWR spent fuel, and feed of actinides to ATWs (thus, loss from spent fuel pools), with values calculated by year, from 1996 to 2100. Inventories of actinides were accumulated in tables by isotope, mass was removed from the ^{241}Pu inventory as it decayed, and that mass was added to the ^{241}Am inventory. Higher actinides from CLWRs (conventional LWR) were accumulated in a single spent fuel inventory, and TULWR (LWR with ThUOX) actinides were accumulated in a separate spent fuel inventory. Actinide feed for ATWs was subtracted from LWR spent fuel inventories at a rate of 1100 kg/yr per GWe ATW (3000 MWth, 35% net efficiency after recirculation of power for the plant). In addition, the feed of isotopes for the ATWs was proportional to the isotopic concentrations in the CLWR and TULWR spent fuel inventories (e.g., if the TULWR pool contained 10% ^{240}Pu and 90% other actinides, then the feed for the TULWR-supporting ATW was 10% ^{240}Pu).

Finally, as a basis for calculations through the year 2100, the accumulated plutonium and higher actinide waste at the end of 1995 (the beginning of the present analysis) was based on 31,952 metric tonnes of spent fuel(7) from a computed 1422 GWe-years of production. This would include approximately 410 metric tonnes of higher actinides from 50 GW-days/tn burnup, or more than one percent of the accumulated spent nuclear fuel from U.S. reactor operations.(8)

Resource Requirements

The calculations of actinide production, transmutation, and accumulation showed that the ThUOX TULWR/ATW fuel cycle can greatly change a future nuclear energy scenario, in terms of resource depletion and production and accumulation of both waste and proliferation materials. In Figure 4 annual resource requirements are shown for natural uranium for CLWRs and natural uranium and thorium for TULWRs that are deployed in accordance with the nuclear power scenario. The apparent fluctuation in the natural uranium requirement for TULWRs is caused by high-enrichment requirements for the first fueling of each reactor (our method assumed that no ^{233}U or Pu would be available from other sources). Each new reactor requires a much larger natural U resource its first year. In the following years, recycled ^{233}U provides some of the needed fissile composition for criticality, so less enrichment is required. This requirement for natural U could be greatly reduced with a reactor design that breeds more ^{233}U versus ^{239}Pu.

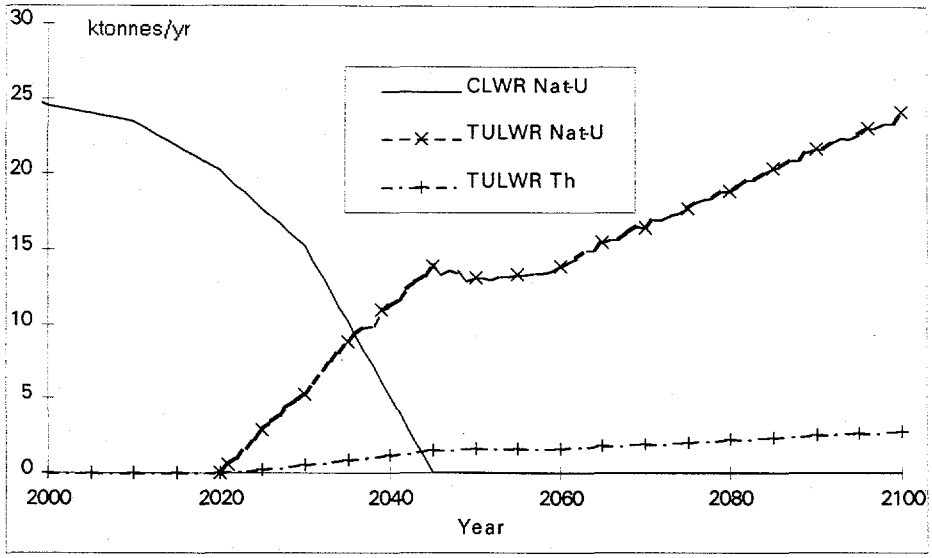

Figure 4. Annual resource requirements for CLWRs and TULWRs.

Figure 4 is a graph of the cumulative resource requirements for both natural uranium and thorium. For comparison, the figure includes cumulative uranium requirements for a scenario with only CLWRs providing growing nuclear electric production through the year 2100. Thus, if we attempt to follow this nuclear growth scenario with CLWRs alone, with no ATWs or TULWRs supplying electricity, the cumulative (U.S.) requirement for once-through LWRs for this moderate-growth scenario would almost equal the world's known (economically recoverable) uranium reserve of 4 million tonnes.(9) If this same growth scenario is applied to the global growth scenario reaching 1000 GWe in 2100, the requirement would be 17.5 million tonnes of uranium, which is more than four times the known reserves (but about equal to the conventional resources). In contrast, the requirement with the TULWR/ATW deployment scenario is just 1.8 million tonnes of U and 0.2 million tonnes of Th (thorium is widely known to be about three times as abundant in the earth as uranium); both are well below current, known, economical world reserves.(10) A similar global deployment scenario of TULWRs and ATWs would require 9 million tonnes of U and 0.7 million tonnes of Th, which are also less than known resources. Thus, the TULWR/ATW concept, with ThUOX-fueled reactors and actinide burning, would prevent future excessive depletion of world resources. However, this analysis also demonstrates that substantial additional savings could be realized with a deployment of a reactor with higher conversion of thorium to ^{233}U.

Proliferation Attributes of TULWR/ATW Pu

Plutonium will accumulate in cooling/storage pools in spent fuel from CLWRs (currently about 30 tonnes) and from TULWRs. This plutonium is of concern not only because of the quantity accumulating worldwide, but also because of the forms of that Pu (in-core, in storage, separated, in MOX fuel, etc.), and because of the "quality" of the Pu, that is, how useful it might be for constructing nuclear explosives. Because of these concerns, the ATW program at LANL has been designed to burn U.S.-generated Pu, plus other actinides, which will both destroy the Pu and produce electricity (one current ATW concept includes thermal to electric conversion of 40%, or about 35% net for an ATW plant). Each ATW will fission about 1100 kg of actinides per GWe produced. However, because of the accumulated inventory and ongoing production of Pu (250 kg/year/GWe), more than 900 tons of Pu will be in storage in the U.S. before deployment of the first ATW in 2020. To compute the removal of actinides from spent fuel, each ATW removed about 1000 kg/yr of actinides from the CLWR or TULWR spent fuel inventory. In Figure 6 the cumulative inventories of Pu in both TULWR and CLWR used-fuel reserves are compared.

Again, if the power growth scenario represented in Figure 1 is supplied by CLWRs alone, without actinide burning or recycle, Pu will accumulate approximately like the upper curve of Figure 6, with a total inventory exceeding 3,500 tonnes by 2100. Although not of the same quality as weapons-grade Pu, and initially protected by the "reactor standard," large quantities of Pu have been identified as a significant proliferation issue.(11)

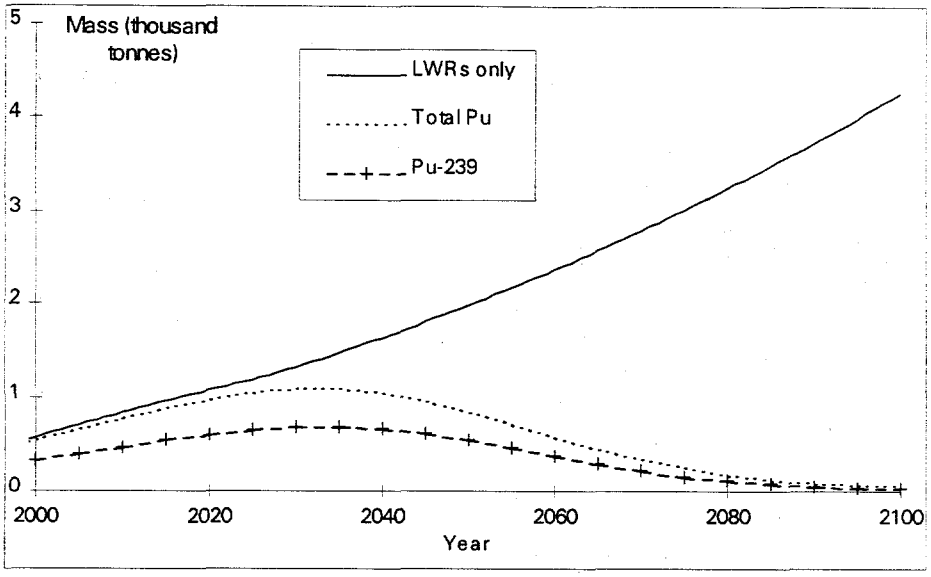

Figure 5. Cumulative natural resource requirements for CLWRs and TULWRs. This figure includes the cumulative requirement if all nuclear energy to 2100 is supplied by once-through CLWRs only (upper line).

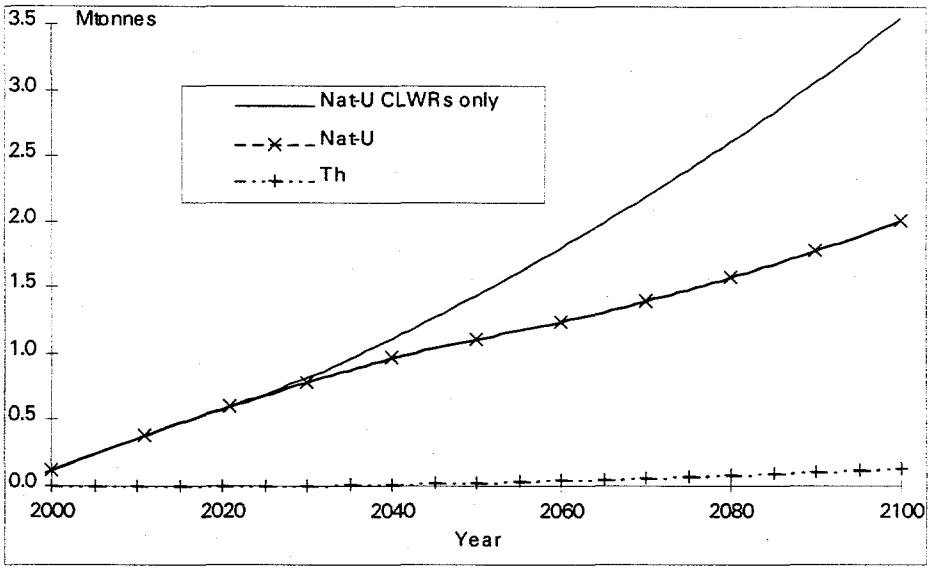

Figure 6. Pu in spent-fuel inventories resulting from an TULWR/ATW deployment scenario with 200 GWe in the year 2100. The upper solid line represents Pu inventory that would accumulate if once-through UO_2-fueled LWRs provide all the nuclear electricity.

In contrast, with the TULWR/ATW deployment scenario, the Pu in inventories of spent fuel is equal to the product of the annual production (per GWe) times 1 to 5 years (the cooling time before

reprocessing) times the total power of all TULWRs. All other spent fuel will be removed for processing for transmutation. The total inventory (see the dashed curve of Figure 6) would be about 67 tonnes in 2100, which is less than 2 percent of the Pu that would accumulate from the once-through fuel cycle. In addition, most of this Pu would be controlled/contained in highly radioactive fuel (less than 5 years decay time) or in processing for feed to ATWs, in contrast to current practices and plans, where spent fuel has been decaying for more than 20 years in cooling ponds, and in the future may be placed in interim storage facilities or in final, underground repositories.

In addition to this greatly reduced quantity of Pu in out-of-core inventories, the Pu produced in ThUOX fuel has a higher source of spontaneous neutron emission and thermal energy. Both of these "qualities" affect the attractiveness or usefulness of Pu for nuclear weapons; therefore Pu created during the scenario examined in the present study will be compared with the attributes of three different grades of Pu: Weapons-grade Pu (W-G Pu), Reactor-grade Pu (R-G Pu), and Mixed-Oxide-grade Pu (MOX-G Pu). These attributes include critical mass, thermal energy, and spontaneous neutron emissions; all of which might affect design, construction, or probability of achieving a given yield. Although criticality and yields of devices that could be created from the Pu from CLWRs and TULWRs were not examined in this study, the tables were used to examine trends and estimate differences between Weapons-grade Pu (W-G Pu), Reactor-grade Pu (R-G Pu), and the Pu that results from the ThUOX TULWR/ATW closed fuel cycle.

The thermal energy production and spontaneous neutron production or source (SNS) from the different isotopes of Pu, in per kg units, as well as the minimum mass of a given isotope of Pu that would be required to create a bare critical assembly; the Bare Critical Mass (BCM), are listed in Table 1 (next page) for each of the isotopes of Pu. While the heat produced by a quantity of Pu is influenced strongly by the 238, 240, and 242 isotopes of Pu (all α emitters), the quantity of Pu required to form a critical assembly is increased only by the 240 and 242 isotopes. Thus, the heat produced by a BCM of Pu will depend on concentrations of the ^{238} Pu, ^{240} Pu and ^{242}Pu. Each of these parameters (heating, SNS, and BCM) will be examined briefly, then products or ratios will be presented and the results interpreted as they apply to usefulness for proliferation. Isotopic compositions of Pu in the final spent-fuel pool from TULWRs is given in Table 2, along with compositions of various grades of Pu. These vales were used to compute parameters that are used to compare proliferation attributes of the different grades of plutonium, which will be presented in discussions in the following pages.

Table 1. Spontaneous neutron emission rate (SNS), heating (computed from data from Reference 12), and critical masses (computed via SCALE, Reference 13) of bare (non-reflected) spheres (BCM) of isotopes of plutonium.

Isotope	SNS (n/s/kg)	Heat (W/kg)	BCM (kg)
Pu-238	2.60E+06	5.6E+02	10
Pu-239	2.2E+01	1.9E+00	10
Pu-240	9.1E+05	6.9E+00	36
Pu-241	4.8E+01	4.2E+00	13
Pu-242	1.7E+06	1.1E-01	92

Table 2. Isotopic compositions (weight percentages) of five grades of plutonium: Weapons grade (W-G), Reactor grade (R-G), Mixed-Oxide Grade (MOX-G), Radkowsky Thorium seed spent Fuel (RTF), and the final TULWR plutonium in the spent fuel pool.

Isotope	W-G (Ref. 14)	R-G (spent fuel) (Ref. 15)	MOX-G (feed) (Ref. 16)	RTF seed (spent fuel) (Ref. 2)	TULWR (spent fuel)
Pu-238	0.00012	0.024	0.019	0.065	0.089
Pu-239	0.938	0.584	0.404	0.465	0.499
Pu-240	0.058	0.240	0.321	0.225	0.181
Pu-241	0.0035	0.112	0.178	0.155	0.098
Pu-242	0.00022	0.039	0.078	0.090	0.086

Figure 7 illustrates the fractional compositions of ^{239}Pu in the spent fuel from CLWRs and TULWRs in the scenario studied herein, as well as the increase in ^{238}Pu concentration in the combined pools. The heat that a given grade of Pu produces is simply the linear combination of isotopic heating values (W/kg, from Table 1) with the isotopic concentrations in that grade of Pu (from Table 2). Thus, a 50/50 combination of ^{238}Pu and ^{239}Pu would produce 280.95 W/kg (560/2 + 1.9/2 = 561.9/2 = 280.95), and a BCM would produce 10*280.95 or 2,810 Watts for many years (the half life of ^{238}Pu is 87.7 years). The heating per unit mass in CLWR Pu and TULWR Pu are shown in Figure 8 along with heating rates for W-G, R-G, and MOX-G Pu. For comparison with a proposed near-term ThUOX fuel cycle, the computed value for the Pu from seed-fuel elements of the Radkowsky Thorium Fuel (RTF) is also included. Again, the isotopic ratios in fed U and discharged Pu for TULWRs change with time, so the upper line fluctuates during rapid new-reactor deployment.

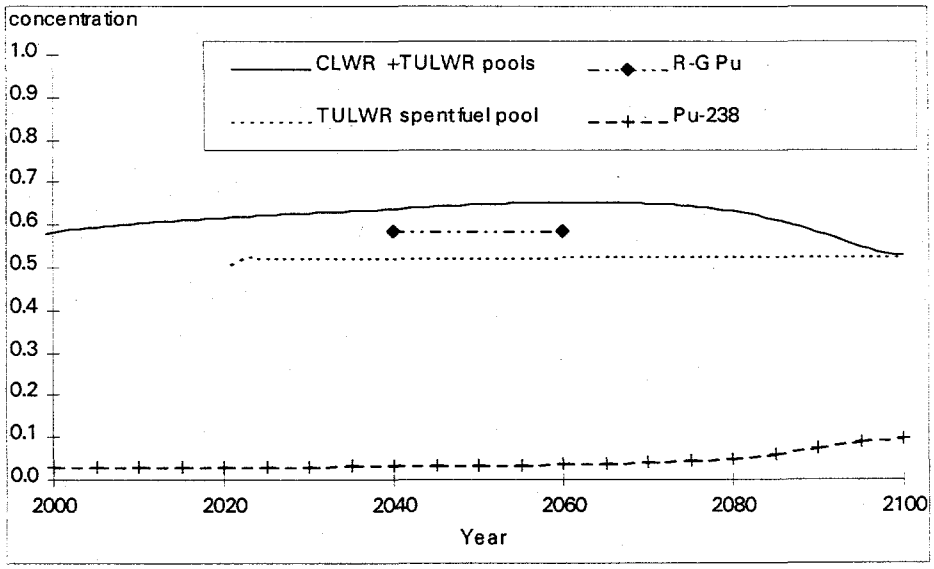

Figure 7. Concentrations of ^{239}Pu and ^{238}Pu in various grades of plutonium. The upper line includes the combined Pu from both CLWRs and TULWRs. From 2000-2020 it is entirely CLWR Pu, and from 2080 to 2100 it is almost entirely TULWR Pu.

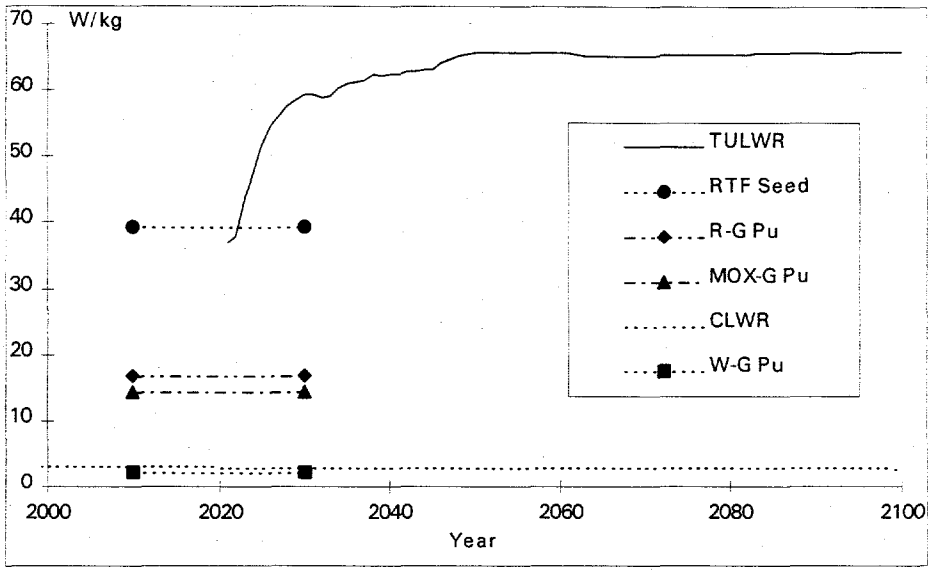

Figure 8. Heat generation in plutonium from CLWR and TULWR spent fuel. For reference, the computed value for the Pu from spent seed-fuel elements of the Radkowsky Thorium Fuel (RTF) is included.

If the bare critical masses and the isotopic concentrations in the various grades of Pu are combined linearly, as before, an index for critical mass is obtained; results are displayed in Figure 9. The Pu from the ThUOX-fueled TULWR/ATW scenario has approximately the same BCM index as the nominal R-G Pu because it has about the same concentration of ^{240}Pu and ^{242}Pu, and this BCM is much larger than the value for W-G Pu. An alternative interpretation of this figure is that the inverse of the BCM provides an indication of a relative number of weapons that could be constructed from inventories of different grades of Pu—a larger value of BCM for TULWR Pu means that fewer weapons could be created from a given mass of diverted spent fuel.

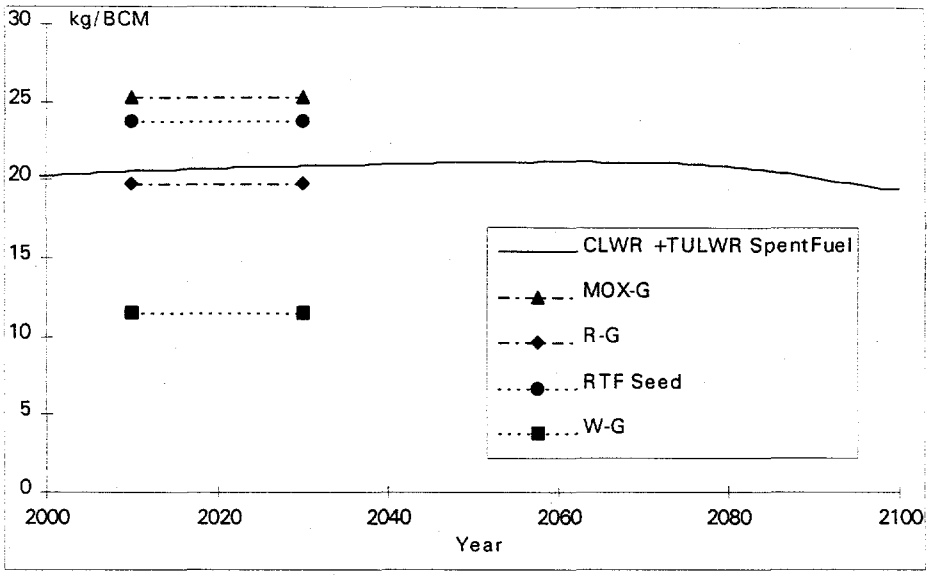

Figure 9. Bare Critical Mass (BCM) index: the mass of a non-reflected critical assembly of a grade of plutonium.

Another index of "usefulness" is produced by combining the heating value with the critical mass index, to obtain an index of alpha-decay heating per critical mass, as in Figure 10. The value shown in this figure indicates a comparison of how much heat would be generated inside comparable weapons. The value for the TULWR Pu, 1200 Watts per Bare Critical Mass, is about 50 times the heat in a critical mass of W-G Pu, and also exceeds the heating in Pu from LWRs, that in MOX, and that in RTF spent-seed fuel. Thus any attempt to build a weapon from this material would require complex heat removal engineering solutions to prevent substantial degradation of weapon performance.

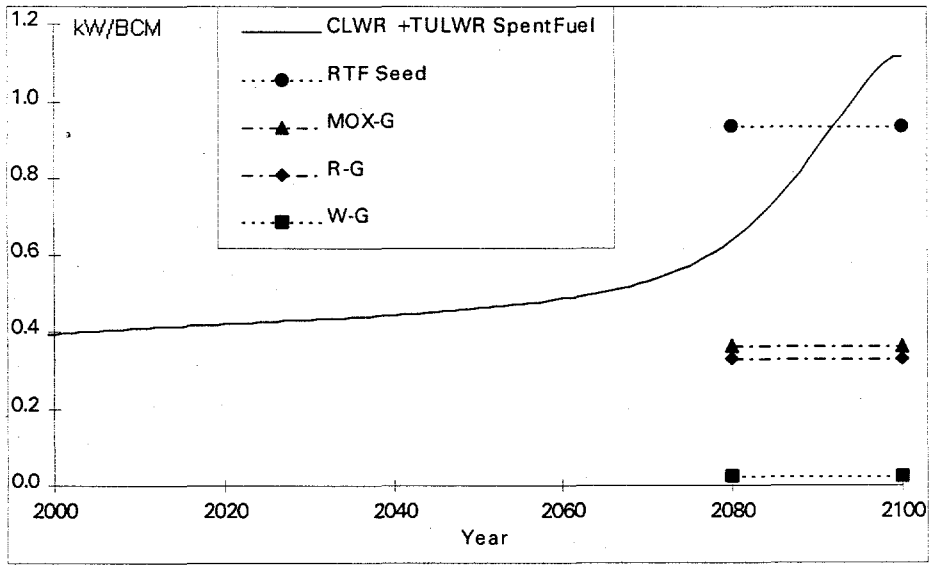

Figure 10. Heat generation per BCM (the heat that would be generated in a bare critical sphere of Pu).

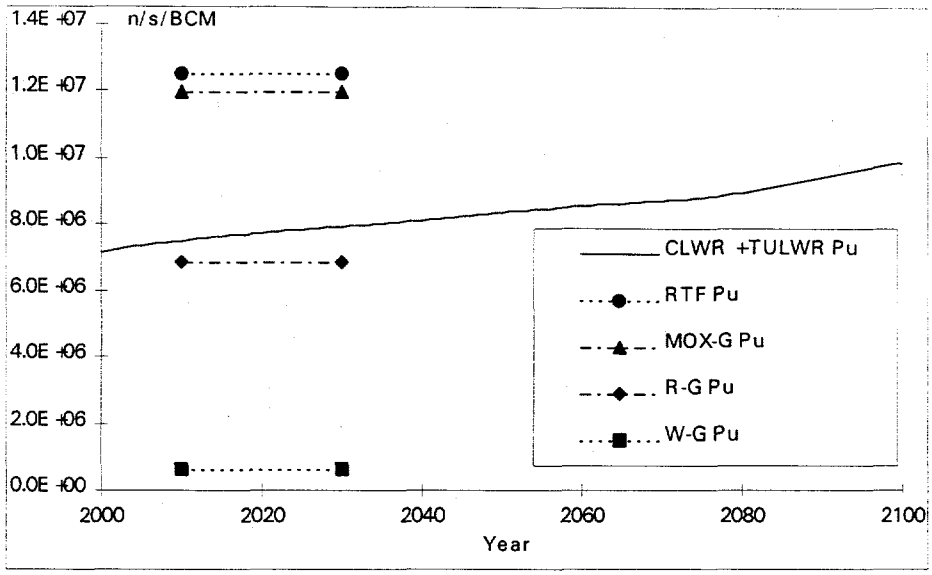

Figure 11. Spontaneous Neutron Source (SNS) in a critical mass of various grades of Pu (n/s per BCM).

Similar to the computation of heat/mass or heat/BCM, the SNS values from Table 1 were linearly combined with the fractional composition of Pu in each process stream to give the spontaneous neutron sources that are shown in Figure 11. The values for CLWR (left portion of the curve) and TULWR (right portion) spent-fuel Pu are both high compared with W-G Pu, and the TULWR Pu emits more neutrons per second than that from CLWRs. Note that the CLWR SNS rate increases with time because Pu-241, which contributes almost nothing to the SNS, decays (to ^{241}Am) with a 14.4 year half-life, which effectively increases the concentrations of other neutron-emitting isotopes.

Fuel Cycle Cost Savings

Although a detailed analysis of fuel cycle costs was not performed for this study, other recent comparisons of once-through thorium-uranium fuel cycles with current LWR fuel cycles have predicted savings of 20 to 30 percent.(17, 2) This savings excludes any additional savings that could be realized by reductions in the mass of spent fuel that requires permanent storage.

Further Studies

The results of systems analyses that were completed for this study have revealed opportunities for optimization and directions for further studies. These might include:

- Optimization of the Th-U fuel cycle to maximize conversion of thorium to fissile ^{233}U and to minimize the production of actinides and the cost imposed by the fuel-cycle-closing ATWs.
- Longer burnup fuel cycles (RTF ThUOX blanket fuel will have a burnup of 100,000 MWd/tonne heavy metal), which will also produce less actinides per unit energy, and a different mix of actinides that would require transmutation.
- Implementation of other Th-U fuel cycles, e.g., high-temperature gas reactors or fast reactors cooled with liquid lead-bismuth (the same coolant as the ATW), which would also produce a different mix of actinides and a different quality of Pu.
- Improved computational methods that include the actual histories of U.S. power plants and options for varying burnup, electrical generation efficiencies, and capacity factors in the future. This might include adding current plans for use of MOX fuel in existing LWRs or in advanced LWRs.
- Coupling of results of these studies to analyses of cost of electricity and to some form of index or prediction of proliferation risk.

Summary

A future nuclear energy scenario that includes new LWRs with thorium-oxide fuel, with follow-on processing and burning of actinides in ATWs, results in a closed fuel cycle that produces smaller quantities of Pu and other actinides than the "standard" once-through LWR fuel cycle. This TULWR/ATW offers other improvements that include reduced depletion of natural resources (50% less natural uranium), smaller volumes and less hazardous waste for disposal (98% less higher actinides), and a lesser "quality" of Pu for proliferation of nuclear weapons (50 times the heat and 15 times the rate of spontaneous neutron emission per critical mass as weapons-grade Pu). Thus, the TULWR/ATW ThUOX fuel cycle should be considered a "less-proliferative" fuel cycle. This scenario should also produce a reduction in costs associated with the fuel cycle, on the order of 20%. In addition, this scenario includes only one ATW for every seven TULWRs, and the ATW will produce electricity for sale as well as savings in terms of the forms and volume of waste for final disposal, so the ATW deployment should have a minimal impact on the cost of electricity.

Topics for further studies have been identified which may point toward opportunities of enhancing this scenario with other types of advanced reactors, fuel cycles, or processing options.

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