LA-UR- 96-1868

CONF-960639--3

Title: **IMPACT OF ADTT CONCEPTS ON THE MANAGEMENT OF GLOBAL PLUTONIUM INVENTORIES**

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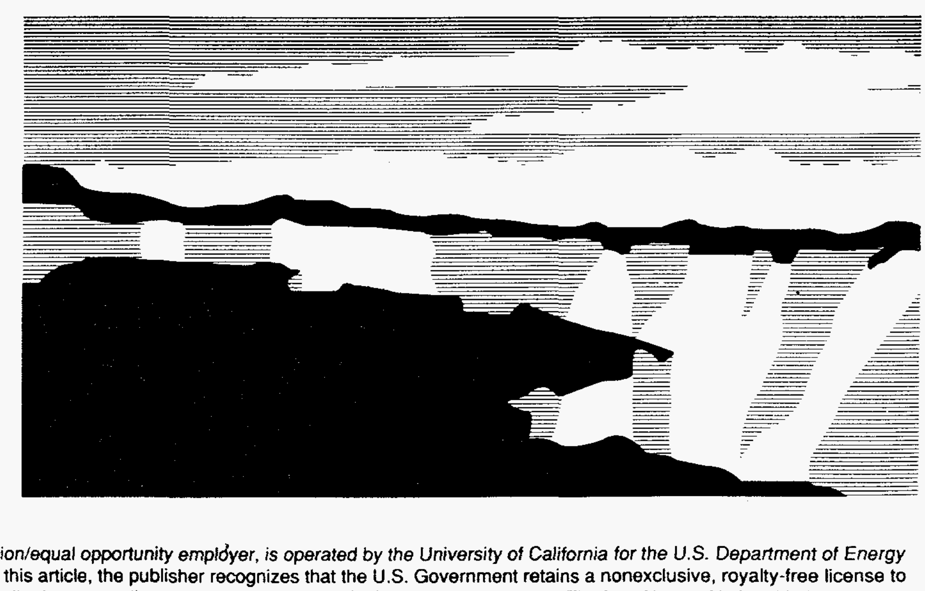
Submitted to: Second International Conference on Accelerator-Driven Transmutation Technologies and Applications
June 3-7, 1996, Kalmar, Sweden



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Impact of ADTT Concepts on the Management of Global Plutonium Inventories

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Abstract. The impact of a number of current and future nuclear systems on global plutonium inventories is assessed under realistic forecasts of nuclear power growth. Advanced systems, such as those employing Accelerator Driven Transmutation Technologies (ADTT) and liquid metal reactors, show significant promise for meeting future plutonium management needs. These analyses also indicate requirements for a higher level of detail in the nuclear fuel cycle model and for development of a metric to more quantitatively assess the proliferation risk of plutonium arising from the civilian fuel cycle.

INTRODUCTION

Recent studies[1,2] by prestigious panels of the National Academy of Sciences and the American Nuclear Society have identified global stocks of plutonium residing in spent fuel stores as being a significant proliferation and waste management issue. The proliferation concern can be characterized in terms of short-term timescales (several decades involving issues such as material diversion, latent capability for creation of large amounts of nuclear weapons, etc.) or on longer timescales (centuries, millennia) where the need to safeguard materials existing in "plutonium mines" may exist. Waste management issues relate to the very long half life (24,000 years) of the major plutonium isotope (^{239}Pu) and its decay into the fissile ^{235}U, both of which lead to long-term criticality concerns. Finally, underlying both of these potential issues are differing global perspectives concerning the value of plutonium contained in spent fuel in terms of its energy content versus costs needed to effectively use it.

This background enumerates many of the reasons that have prompted studies and analyses within the Nuclear Vision Project[3] at Los Alamos National Laboratory aimed at examination of the future dynamics of plutonium inventories and the impact of technological options on their management. This paper presents results from models of the nuclear fuel cycle which have been used to examine the impact of accelerator-driven transmutation technology (ADTT) systems on plutonium inventories. It also compares ADTT results with the performance of other nuclear systems on such inventories. The analysis also includes use of models to estimate future nuclear power growth on a region-resolved basis in order to obtain indications of future plutonium growth within major world geographic regions as well as globally.

This paper provides a brief description of the models used (with emphasis on the representation of the nuclear fuel cycle) as well as parameters used to provide a top-level description of respective nuclear systems investigated here. Results from the analysis are presented, and the performance of ADTT systems is compared with other strategies for plutonium inventory management and reduction. Finally, directions for future research activities and needs are suggested.

MODELS AND ASSUMPTIONS

An underlying assumption of the present analysis is an effort to provide a credible assessment of the future magnitude of nuclear power globally, from which plutonium inventories in spent fuel are then determined. This assumption extends earlier analyses [4] performed at Los Alamos where global nuclear power was assumed to remain at the current level (approximately 325 GW_e) over the next hundred years. Results from those earlier analyses indicate mid-century global plutonium inventories of 3,000 to 5,000 tonnes discharged in spent fuel, depending on fuel burnup levels assumed (33,000 MWd/tonne or 50,000 MWd/tonne). To obtain future levels of global nuclear power for the present analysis, an approach built around a global energy modeling framework developed by Pacific Northwest Laboratory(PNL)[5] was used. This model uses an E^3 (energy, economics, environment) approach that competes in a world market fossil, solar (and other renewables), and nuclear primary energy sources while tracking key environmental concerns associated with each. Through this model framework and simpler more analytical approaches[6], this analysis relates global energy demands based upon relationships between population growth, global and regional economic goals (gross national product (GNP) per capita), and energy utilization (annual energy demand per GNP). The effort also has involved improving and expanding the simple structure for describing the nuclear fuel cycle in the PNL model with a more robust, aggregated nuclear fuel cycle model that incorporates both economics and nuclear material flows. The final component of this effort is the development of a multi-regional global nuclear materials flow model that is embedded in a realistic portrayal of energy futures estimated to the year 2100 under assumptions of cost competitiveness and market equilibrium.

The second model used in this analysis is a more detailed representation of the fuel cycle associated with a variety of nuclear systems under investigation. This model incorporates the various plutonium-related components and operations of the nuclear fuel cycle (fission power systems, spent-fuel cooling, reprocessing, fabrication, storage, and disposal) as well as the uranium components (mining, milling, conversion, and enrichment). The material inventory flows for the plutonium-related components are illustrated in Figure 1. Note that the operations where plutonium is available for dedication to fuel cycle and production alternatives are accounted for separately from that utilized in fission power systems. Nuclear power systems are parametrically modeled as power systems: rated power, availability, efficiencies, plant life, etc. All fuel cycle operations are parametrically modeled as material processing systems: inventories, process separations, isotopic shifts, cooling times, etc. The nuclear material inventories are characterized by mass, form, element or element group (plutonium, uranium, minor actinides, fission products), and isotopics.

Total nuclear system deployment is prescribed both by a nuclear power scenario (growth, constant level, decline) and replacement/decommissioning of retiring systems. Individual system deployment is defined by system mixes, initiation dates, and phase-out times. Deployment is also constrained by resource (e.g., plutonium) availability and retirement schedules. For nuclear scenarios that contain net consumers of plutonium (LMRs or ADTT systems), the model will determine an asymptotic burner deployment strategy which will minimize the amount of "available" plutonium.

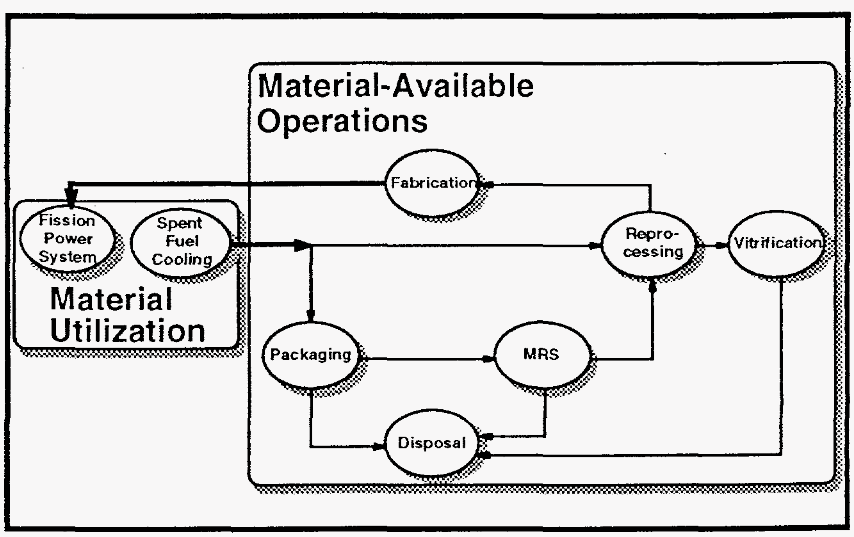

Figure 1. Plutonium-related fuel cycle model components used for analysis.

In this paper, the following nuclear system scenarios were modeled to assess their impact on global plutonium inventories:

1) *Scenario 1* - Low-enriched uranium (LEU) fueled light water reactors (LWRs) plus mixed uranium/plutonium oxide (MOX) fueled LWRs deployed beginning in the year 2000. MOX-fueled LWRs are built in a 1-to-7 ratio with LEU-fueled LWRs. This implementation ratio mirrors the international MOX recycle strategy of today and projects it forward in time. This scenario is the "reference" global plutonium management case. The MOX-fueled LWRs are modeled as plutonium single-recycle systems with one-third core loadings of 5% plutonium-bearing MOX.
2) *Scenario 2* - LEU-fueled LWRs plus an aggressive introduction of the MOX-fueled LWRs beginning in the year 2000. All LEU-fueled LWRs that are replaced or new nuclear systems that must come on line to meet overall nuclear power capacities are the MOX-fueled systems described above.
3) *Scenario 3* - LEU-fueled LWRs plus a more modest introduction (50% of new and replaced) of the MOX-fueled LWRs beginning in the year 2000; the MOX-fueled LWR deployment ceases after 30 years with subsequent phaseout. Additionally, liquid metal reactors (LMRs) are deployed beginning in 2020 with equal deployment of LEU, MOX, and LMR systems. The LMRs are assumed to be burner systems (conversion ratio of 0.6) with integral fuel processing. Since these systems are net consumers of plutonium, their eventual deployment is constrained by the plutonium availability dictated by LEU-fueled LWR discharge and decommissioned systems.
4) *Scenario 4* - Identical to Scenario 3, but net-power-producing accelerator driven systems are deployed starting in 2020 instead of the LMRs.

All of the above cases were examined under a scenario of an annual two percent growth rate in nuclear power globally over the timeline of the analysis. This assumption lies between the range of 1–3 percent per year growth[7] obtained from the global E^3 model described above. (One percent is estimated as the baseline scenario for growth; three percent could result from efforts (carbon tax implementation) to curtail greenhouse gas emissions from burning of fossil fuels). This range of nuclear energy growth also agrees with results from other recent analyses[8] but differs from nuclear energy growth projected for the United States by the Department of Energy. The parameters used to describe the nuclear systems that comprise the four scenarios described above as well as other fuel cycle inventory assumptions are provided in Table 1.

Table 1. Nuclear system parameters used in the present analysis

Fission Power System Parameters	LEU-Fueled LWR	MOX-Fueled LWR	LMR Burner System	ADTT Burner System
Rated power (MWe)	900.0	900.0	900.0	900.0
Average availability (%)	70.0	70.0	70.0	70.0
Thermal conversion efficiency (%)	32.5	32.5	40.0	34.0*
Fuel burnup (GW-d/MTHM)	50.0	30.6	-	-
Fuel specific power (MWt/MTHM)	37.5	37.5	14.8	6030.0
Spent fuel cooling time (y)	1.0	1.0	1.0	1.0
Plutonium Inventory Parameters				
BOL Pu Inventory (MT/GWe)	0.	1.95	9.65	1.98
EOL Pu Inventory (MT/GWe)	1.37	2.13	12.30	2.54
Annual Pu Charge (MT/y)	0.	0.61	0.31	0.90
Annual Pu Discharge (MT/y)	0.25	0.66	0.	0.

* Based on 15% recirculating power fraction

RESULTS

Figures 2–5 illustrate global plutonium inventory dynamics projected for the four scenarios described above. Each figure includes curves representing other inventory-related data. Labels in each figure indicate the total plutonium inventory existing in the global nuclear fuel cycle as a result of implementation of a given technology scenario (total), the portion of the plutonium inventory resident in nuclear systems (internal), that part of the total plutonium inventory assumed in cooling after discharged from LWRs or other nuclear systems (cooling), and the "available" curve which is that material available for dedication to fuel cycle and production alternatives such as fueling additional plutonium-burning systems. In Scenarios 3 and 4, which include net plutonium consuming systems, the latter curve is driven to values close to zero as a result of the burner deployment assumptions of the model that were described above.

Under the growth scenario for nuclear power assumed in this study, the implementation of LEU/MOX LWR systems following strategies currently used could not keep pace with predicted plutonium inventory growth. Figure 2 indicates not only the lack of significant impact but also shows that "available" plutonium continues to grow. This results from the inability of the MOX-fueled LWR plutonium utilization to consume the discharged plutonium produced from the growing numbers of LEU-fueled LWRs. This inventory is locked up in spent fuel, which means that some short-term impediments to proliferation are present. However, the long-term proliferation hazards and waste disposal concerns associated with large plutonium inventories are not adequately addressed using this strategy.

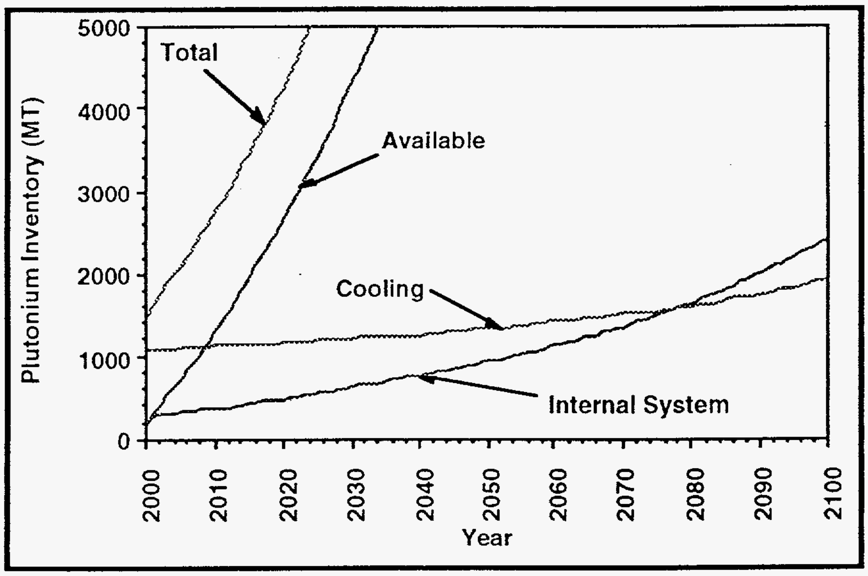

Figure 2. Inventory results, LEU-fueled and MOX-fueled LWR system mixture in the ratio of 7:1 (Scenario 1).

A more aggressive implementation of MOX-fueled reactor cores can have a significant impact on plutonium inventories, as is illustrated in Figure 3. The level must be at, or near, complete MOX-fueled system replacement for each retiring LEU-fueled LWR or one that must be built to maintain the projected nuclear power growth curve. In this instance, a fortuitous balancing occurs between plutonium produced as a result of new reactor operation and that burned in newly commissioned MOX-burning LWR units. Using this strategy, the total plutonium inventory is reduced by mid-century to a value less than one half of that resulting from Scenario 1 and one third the value of that resulting from no action to recycle plutonium. Approximately one half of the total plutonium inventory is contained within reactor cores. The overall "available" inventory in this scenario remains approximately constant at a worldwide level of 1000 to 1500 tonnes. The existence and magnitude of the "available" plutonium inventory appearing in Figures 2 and 3 indicate that scenarios involving use of additional nuclear system technology would be needed to minimize, and ultimately reduce effectively to zero, plutonium in this category. Scenarios 3 and 4 represent strategies aimed at aggressive minimization of this available plutonium parameter. Figure 4 illustrates plutonium inventory impact resulting when LMRs are deployed as described above. This strategy effectively minimizes to near zero the worldwide inventory of available plutonium. The impact on the overall plutonium inventory is about the same as that for the aggressive MOX-fueled LWR implementation scheme discussed previously. In this scenario, most of the plutonium inventory is tied up in operating reactor cores as a result of the large inventory per LMR (13 tonnes/GW_e) needed for operation. (Of all plutonium forms, inventory tied up in nuclear system cores is the most secure against theft/diversion.)

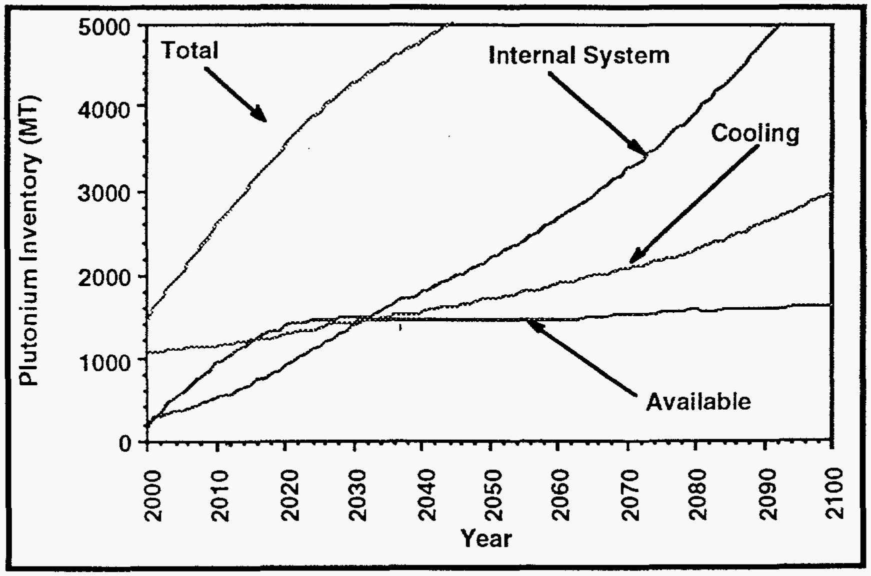

Figure 3. Inventory results from aggressive implementation of MOX-fueled LWR systems (Scenario 2)

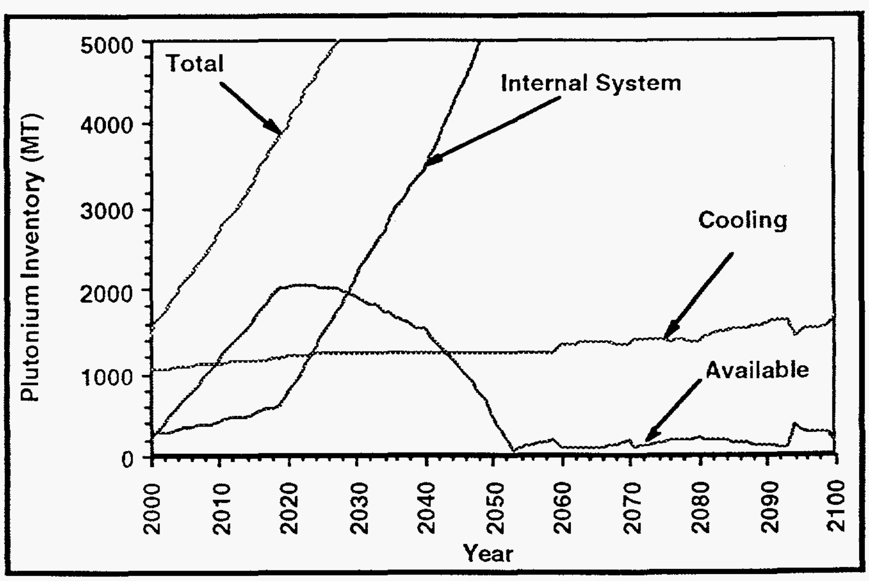

Figure 4. Inventory results from the described mixture of LEU/MOX LWRs and LMRs (Scenario 3).

An additional consideration is the relative mix of LWRs and plutonium burning systems that must be implemented to achieve the results described earlier. Figures 7–9 illustrate the number of systems needed for Scenarios 2 -4. In Figure 7 (corresponding to Scenario 2) the number of MOX-fueled systems overtakes LEU fueled-LWRs existing globally by the year 2030, so that after that point, the entire global fuel cycle is based on MOX-fueled systems.

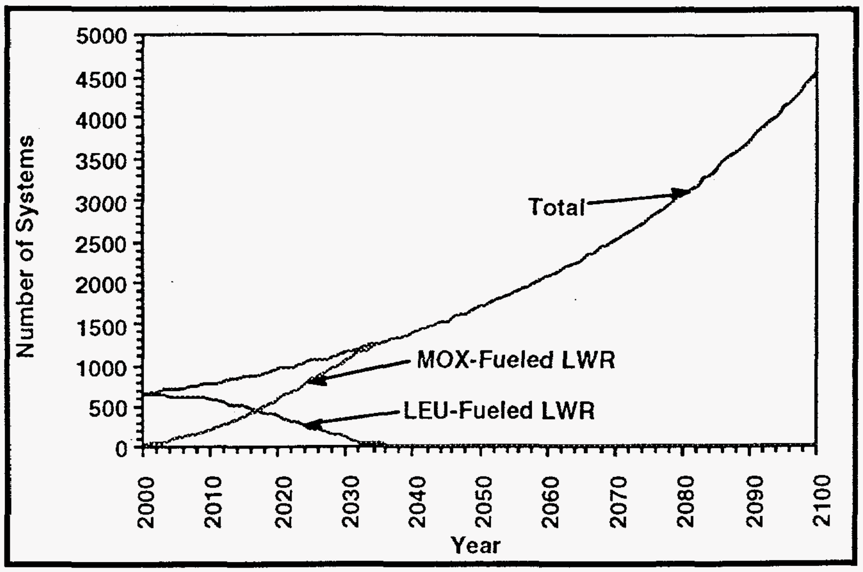

Figure 7. Number of nuclear system types for the aggressive MOX-fueled LWR implementation (Scenario 2).

Based on the preliminary estimates made from the global E^3 model[7] used in part of this analysis as well as other forecasts, the growth in nuclear power by the middle of the 21st Century could occur in nations and regions significantly different than those nations that developed nuclear power during its first forty to fifty years. Also, the installed capacity in those nations is predicted to be several times higher than that existing in the US or OECD nations. Under this aggressive MOX implementation scenario, the full spectrum of fuel cycle facilities (enrichment, reprocessing, MOX fuel fabrication) would have to exist in regions characterized as "developing," or significant transportation of nuclear material (spent fuel, fabricated MOX fuel) would have to occur between those regions and facilities located in presently established nuclear energy states.

Figure 8 provides similar results for the scenario where an LWR/LMR mix is used for global plutonium management and minimization. Not unexpectedly, the number of LMR systems needed for plutonium management is large and reaches a maximum number that is commensurate with the number of LWRs needed in this scenario. These results require an average build rate of approximately 20 LMR units per year. This build and implementation rate is probably unrealistic for an advanced technology until well after 2050. This rate is, however, consistent with assumptions made in the recent EPRI study[8] on the economic potential of the breeder that indicates build rates for LMRs of 10 to 20 per year around the mid-21st Century, increasing to rates greater than 50 per year in the latter quarter of the century. This large predicted growth in LMRs in this model, coupled with estimates[7] of regions where significant nuclear growth is expected, means that this advanced technology would probably be deployed in significant amounts in developing countries (where population growth and energy demand would be largest).

Finally, Figure 9 indicates the number of nuclear units for the scenario involving ADTT systems. After an aggressive build-up initiative involving rates of 20 per year (needed to work off past plutonium accumulations and to account for phase out of MOX units), the build rate in the latter part of the 21st Century levels off to a rate around 10 per year.

The results for the ADTT case are given in Figure 5. Application of this system also minimizes (zeroes) inventories of available plutonium and lowers the overall plutonium inventory by a factor of three to four by 2050 and by a factor of ten by 2100. The residual level is comprised of the LWR discharge amount assumed in cooling before being fed into accelerator systems and the amount in nuclear cores (including both accelerators and LWRs). Figure 6 shows results on the overall plutonium inventories when the inventory per accelerator system is reduced by a factor of ten. The impact is minimal, indicating that most of the inventory is tied up in the LWR systems that the ADTT systems are supporting.

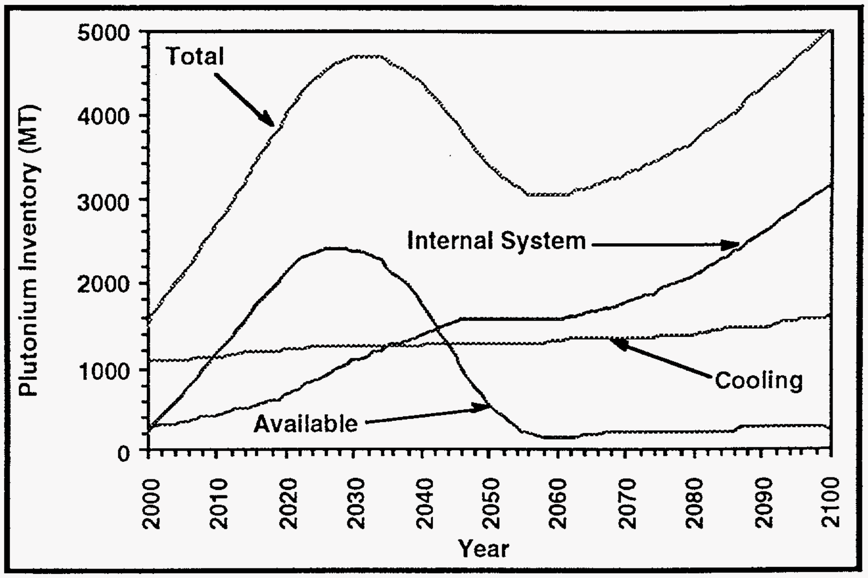

Figure 5. Inventory results from LEU/ MOX LWRs and ADTT units. (Scenario 4)

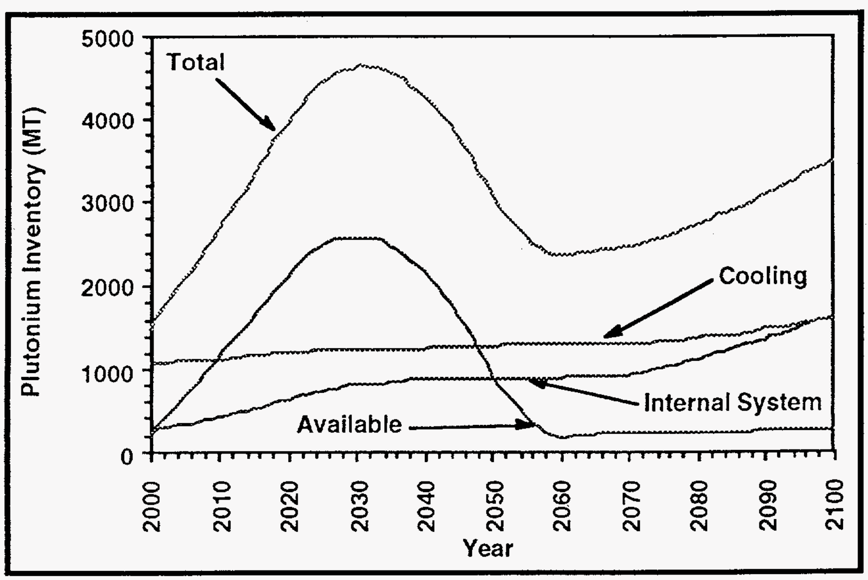

Figure 6. Same as Figure 5 except ADTT inventories are reduced by a factor of 10.

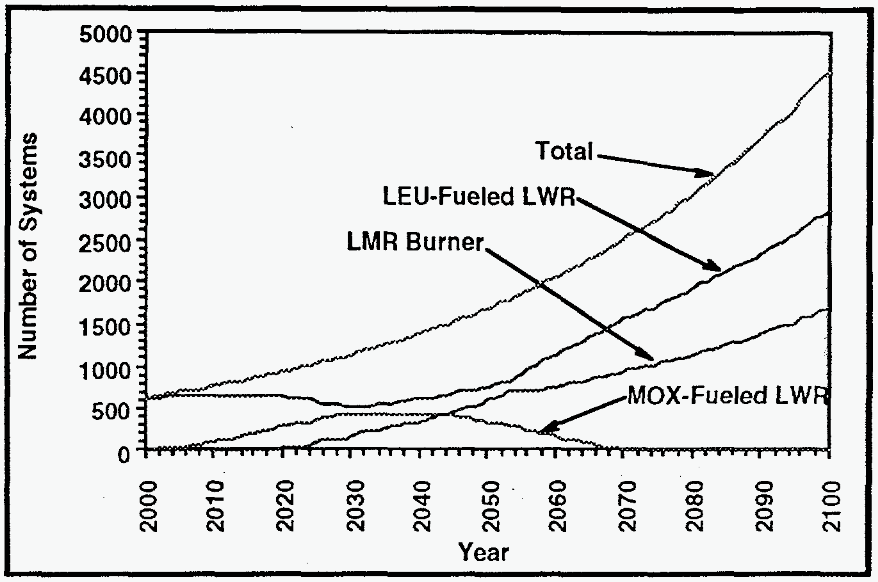

Figure 8. **Number of nuclear system types for the scenario of LEU/MOX LWRs and LMRs (Scenario 3)**

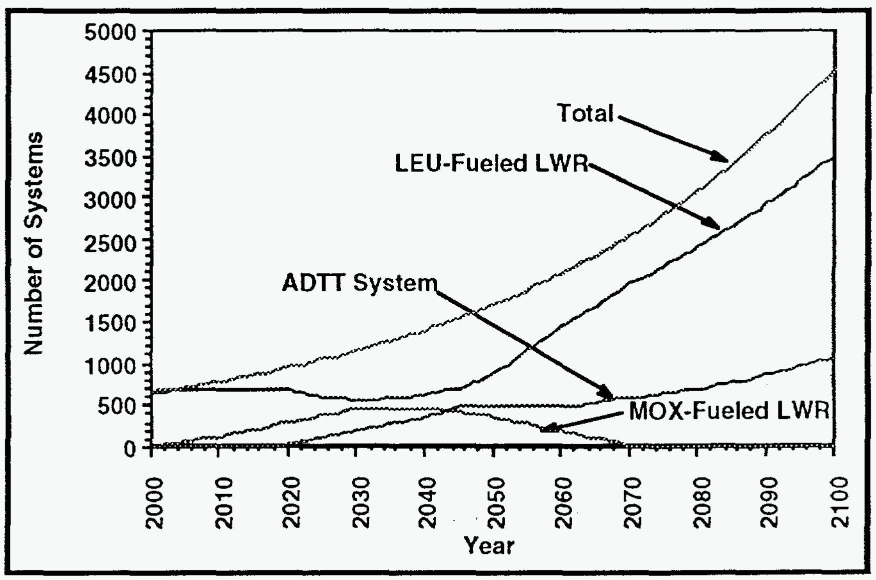

Figure 9. **Number of nuclear system types for the scenario of LEU/MOX LWRs and ADTTs (Scenario 4)**

DISCUSSION

The scenarios examined here provide an initial basis for examination of the behavior of future global and regional plutonium inventories as well as the impact of selected technologies on reducing them. The list of technologies examined in future studies could be expanded to include reactors such as the high-temperature gas cooled reactor, new fuel approaches such as those involving evolutionary MOX or non-fertile fuels for LWRs[9], further mixtures and combinations of those systems with the ones examined here, and advanced fuel cycle variants.

However, a significant need exists to bring these analyses to the next level of detail in the fuel system modeling and to expand such results to include more quantitative measures of proliferation risk reduction or waste impact (beyond the total global inventories examined here). For example, the fuel cycle model can and should be expanded to include more detail in major fuel fabrication and fuel reprocessing components to indicate time-dependent inventories of materials occurring in these steps. This next level of detail also would provide information concerning numbers (and potentially indications of locations) of the large facilities that must support these operations. For example, at least 30 to 40 large reprocessing plants (1000 tonnes heavy metal throughput/year) and 300 large MOX fuel fabrication plants (300 tonnes heavy metal/yr) would be required worldwide to implement most of the scenarios examined here. This information, coupled with results coming from the modified PNL energy model[7], could allow extension of work[10] on the construction of siting and regional fuel cycle scenarios. Such information could also be coupled with other efforts underway, such as the analysis and definition of International Monitored Retrievable Storage System (IMRSS)[11] sites that could exist in several regions and which would provide secure storage for spent fuel and material needed to fuel plutonium burning systems.

The quantitative understanding of how to measure plutonium proliferation risks and waste management impacts (in terms of form, quantity, and function) from such analysis is a more fundamental challenge. For all systems examined here, the amount of plutonium existing globally can still be viewed as significant from proliferation, diversion, and waste disposal perspectives. Taking one view (possibly viewed as extreme but utilized in recently published analyses[12]) pertaining to proliferation and diversion, the amount of plutonium existing in the cycle is enough to make thousands of nuclear weapons if a nation or sub-national group thought the civilian fuel cycle offered the most attractive route to such ends. However, most, if not all, of plutonium residuals are tied up inside inaccessible nuclear system environments (reactors, accelerator-based systems) or in facilities (storage, reprocessing, fabrication) that would be under strong intrinsic national or international safeguards.

This discussion points to the need for development of a metric or metrics that could be used to provide a more absolute basis for judging individual nuclear system and alternative fuel cycle performances or for determining the relative performance of such systems in terms of their impact on proliferation, diversion, and waste disposal. Ingredients of such a methodology could involve assessment of the relative risks associated with various components and operations of the nuclear fuel cycle that would then be projected onto a basis of requirements functions. This general approach has been used in assessments of health risks (see Reference 13) comparing once-through and partitioning/transmutation cycles for nuclear waste management and in fuel cycle proliferation risk assessments (see Reference 14). In the work outlined by Silvennoinen and Vira[14], a number of criteria were defined relating to resources (time and money) and opportunities (technical ease, weapons material quality) existing within the civilian nuclear fuel cycle for nuclear materials diversion. Utility functions were defined that were correlated with various routes occurring within the fuel cycle to create weapons usable materials. These functions were driven by material amounts and, if applied to this analysis, could lead to similar and inclusive results because of the large inventory of materials involved in the global or regional problem. However, this work does provide a start towards defining a broad range of metrics that can be extended to embody time-related functions (e. g., time to acquire material for diversion), the concept of "just-in-time" inventories (so that feed from or to large material manipulation operations do not create situations where inventories inadvertently accumulate) and finally measures related to risks associated with other components of the fuel cycle involving transportation among facilities, residence in a nuclear system core, cooling, etc.

CONCLUSIONS

This work has compared ADTT systems with other strategies for management, use, and reduction of global stocks of plutonium in spent fuel. Subcritical ADTT systems, or critical systems embodying similar operational features, are attractive for such tasks, both from the perspectives of inventory reduction and scenarios for system implementation. However, results from this analysis show the need to investigate any plutonium management/minimization system in more detail so as to understand the functions, operations, and complexities needed for implementation in the nuclear fuel cycle. The results of this analysis (that show large residual levels of plutonium remaining in the world even after such systems are implemented) indicate the need for development of suitable, (and hopefully) quantitative metrics for understanding and evaluating their capability to meet proliferation prevention and waste management objectives.

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