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Title:

Reduction of Worldwide Plutonium Inventories Using Conventional Reactors and Advanced Fuels: A Systems Study

Author(s):

R. A. Krakowski, C. G. Bathke, P. Chodak III

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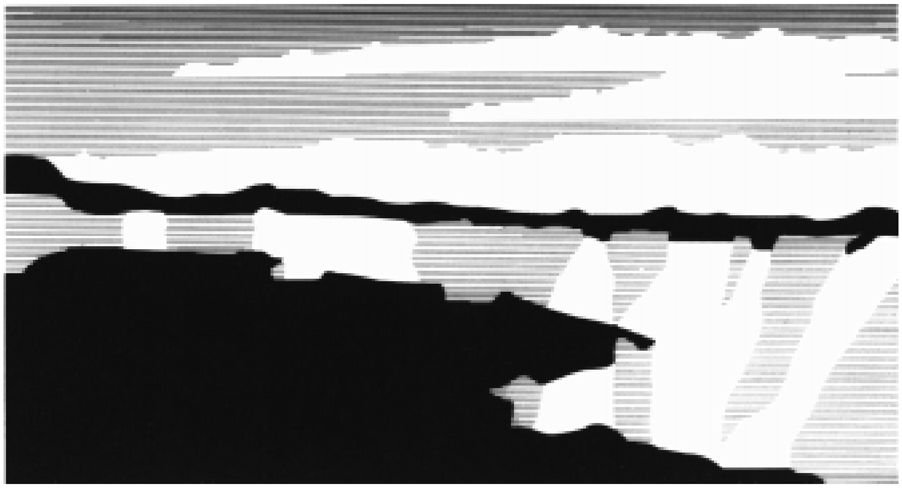

REDUCATION OF WORLDWIDE PLUTONIUM INVENTORIES USING CONVENTIONAL REACTORS AND ADVANCED FUELS: A SYSTEMS STUDY

R.A. Krakowski, C.G. Bathke, and P. Chodak, III
Technology and Safety Assessment Division
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
Tel: 505-667-5862 FAX: 505-665-5283 e-mail: krakowski@lanl.gov

ABSTRACT

The potential for reducing plutonium inventories in the civilian nuclear fuel cycle through recycle in LWRs is examined by means of a cost-based plutonium-flow systems model that includes an approximate measure of proliferation risk. The impact of plutonium recycle forms is examined, including the introduction of nonfertile fuels into conventional (LWR) reactors to reduce net plutonium generation, to increase plutonium burnup, and to reduce exo-reactor plutonium inventories.

I. INTRODUCTION

Plutonium management is a strong and common linkage between many of the complex issues that impact the nuclear fuel cycle[1,2]. This scoping study addresses in broad economic and proliferation terms one approach to managing plutonium in the civilian fuel cycle. Specifically, consideration is given to recycle in thermal-spectrum reactors using mixed plutonium-uranium oxides (MOX) and/or nonfertile fuels (NFFs, *e.g.*, plutonium oxides incorporated into an oxide matrix that is devoid of uranium, like calcia-stabilized zirconia[3]). The combined use of MOX and NFF in transitioning from the former to the latter is also considered (*e.g.*, evolutionary mixed oxides, EMOX = MOX + NFF). This direct, albeit short-term, approach, offers a degree of flexibility in addressing key issues by: a) reducing the plutonium being generated in conventional reactors; b) providing a more effective means to transform excess weapons plutonium; c) reducing inventories of plutonium residing in spent fuel; and d) lowering plutonium inventories in closed fuel cycles of the future needed for nuclear energy to enter a sustainable regime characterized by low inventories of “idle” plutonium.

A three-pronged approach to assessing the merits and limitations of MOX/EMOX/NFF utilization in thermal reactors is being pursued[3]: a) reactor-core physics analyses of NFF utilization in existing (LWR) reactors, including safety (stability, temperature coefficients of reactivity, power peaking, *etc*.) and fuel neutron economy (burnable poisons, fuel lifetimes and burnups); b) materials assessments (fabrication and the relationships between achieving desirable physical properties, irradiation lifetimes and the use of existing fabrication processes); and c) systems studies (fuel cycles and impact on worldwide plutonium inventories in a range of forms; fuel-cycle economics; uranium resource impacts; minimized short-term and long-term proliferation risk). Progress in the latter area is reported herein, with Ref. 2 elaborating on the model used and the results generated.

II. MODEL

Using aggregated reactor-core parameters, these studies use a dynamic model of global plutonium flow that is driven by a range of nuclear-energy growth scenarios.[4,5] Figure 1 gives a diagram of the plutonium flows being modeled, and Fig. 2 depicts operating

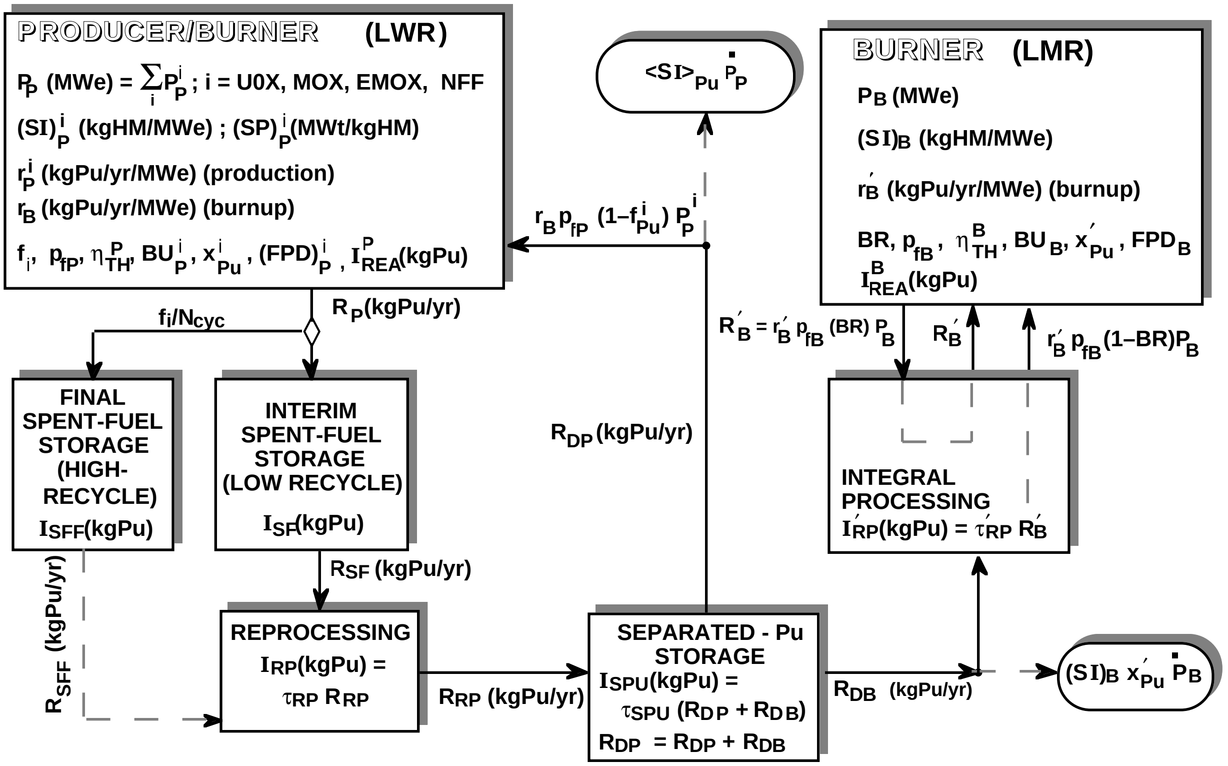

Figure 1. Global plutonium flow model for a system comprising plutonium producers (LWRs) and plutonium burners (FBRs).

scenarios for introducing the MOX/EMOX/NFF sequence. Plutonium inventories are monitored over the ~100-year computational time in five (globally) aggregated forms: a) in-reactor (REA); b) spent fuel forms that are recyclable in LWRs (SF); c) spent fuel forms that are not (efficiently) recyclable in LWRs (SFF); d) reprocessing (REP); and e) separated forms (SPU), including unirradiated MOX/EMOX/NFF. The impact of a range of operational MOX and NFF core fractions and levels of uranium recycle are also examined in terms of the relationship between global uranium resource and price.[6] Preliminary estimates of inventory, economic, and proliferation-risk impacts are reported. Although the model described in Ref. 2 and Fig. 1 includes options that utilize plutonium, particularly the SFF forms, in fast-spectrum burners (FSBs, *e.g.*, LMRs or accelerator-driven systems), only results based on conventional LWRs are reported here.

The growth of aggregate nuclear capacity exogenously follows specific scenarios generated by more detailed models.[4,5,7] The model used herein approximates an aggregated nuclear world and associated plutonium flows and inventories using a single differential equation to describe the plutonium inventory in two spent-fuel forms, I_{SF} and I_{SFF}(kg), along with material residence times, τ_j(yr), at key points in the global nuclear fuel cycle (Fig. 1, *e.g.*, j = REP, SPU, REA).

The simplified model used to evaluated plutonium inventories in spent fuel arising from the uranium oxide (UOX) and MOX/EMOX/NFF parts of the core remains to be calibrated with detailed neutronics and fuel-cycle computations.[3,8] Specifically, net plutonium concentrations in either UOX or

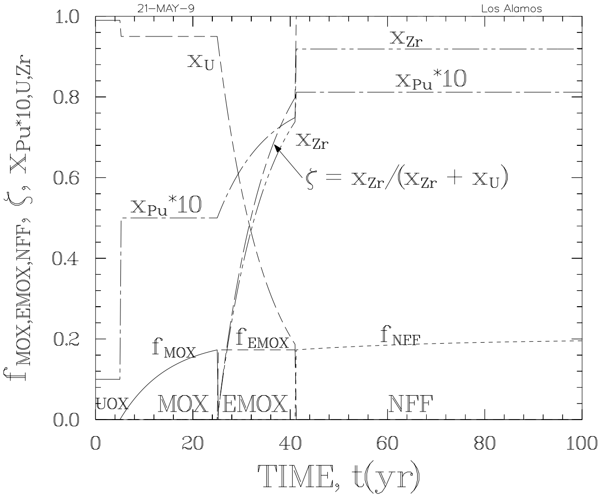

Figure 2. Core-segmentation/composition model, showing full NFF scenario; time nominally begins ~1995.

MOX/EMOX/ NFF parts of the core at end-of-life (EOL) are assumed to equal a constant that is proportionately (linearly) decreased according to the uranium content in the respective core sections. The beginning-of-life (BOL) plutonium concentrations in the MOX/EMOX/NFF parts of the core are proportionately and moderately increased as uranium is replaced with zirconium (Fig. 2). The EOL concentration of this “driver” plutonium is determined from an exogenous burnup, BU(MWtd/kgHM), which is corrected for: a) density variations incurred during any MOX → EMOX → NFF transitions (Fig. 2); and b) the fraction $1 - f_{Pu}$ of all fissions in a given (UOX or MOX/EMOX/NFF) region occurring in the “driver” fuel (*e.g.*, ^{235}U in UOX or BOL plutonium in MOX/EMOX/NFF).

The results presented herein focus on tradeoffs related to a range of LWR operating scenarios. These operating scenarios are defined primarily by the fraction of the core, f_i, that uses recycled plutonium and how the volume of the core that is not conventional UOX is varied in magnitude (*e.g.*, $f_i = 0.0$ is a once-through LWR) and in composition [*e.g.*, i = MOX (mixed plutonium and uranium oxide); i = EMOX (a mixture of plutonium, uranium, and non-fertile (NF, *e.g.*, zirconium) oxides identified as “evolutionary” MOX; and i = NFF (a mixture of non-fertile and plutonium oxide)]. These core-segmentation/compositional options, along with material balances, resource models, costing algorithms, and proliferation risk indices, are elaborated in Ref. 2.

III. RESULTS

The fuel-cycle scenarios considered are once-through (OT) LWRs, plutonium recycle (MOX) in LWRs, and an evolution through EMOX to cores operated with some ultimate fraction of NFF (Fig. 2). The key exogenous variables are: a) uranium resource grade[6] (CR = Conventional Resources, KR = Known Resources, or TR = Total Resources); b) uranium enrichment tailings concentration; c) non-driver fission fraction; d) MOX/EMOX/NFF core volume fractions; e) number of MOX recycles; and f) introduction times and implementation rates of specific fuel cycles arrayed on Fig. 2. Results focus primarily on: a) the buildup of plutonium inventories in the five forms listed on Fig. 1; b) costs associated primarily with the fuel cycle in the form of incremental additions to the cost of electricity, ΔCOE(mill/kWh), or present worth of fuel-cycle charges over the ~100-year period of this computation, PV_{FC}; and c) proliferation risks associated with each plutonium form, as measured by the time-discounted and form-weighted integrated accumulation, PRI(ktonne yr).[2]

To facilitate comparisons, a base case is defined using a MOX core volume fraction that exponentially achieves an asymptote $f^f_{MOX} = 0.3$ with a rate λ_{MOX}(1/yr). After giving (inventories, costs, PRIs) results for the OT/LWR ($f^f_{MOX} = 0.0$) case, similar results for the $f^f_{MOX} = 0.3$ base case are reported (Sec. III.A.). Section III.B. then summarizes results that are pertinent to variations on the MOX and NFF cores, with an emphasis given to the former. All results are based on a single nuclear energy growth scenario described by a nominal growth rate of ~1.0%/yr and reaching a nuclear electric market share of 1000 GWe by the year ~2100.

Since the MOX (or EMOX/NFF) core fractions for all scenarios considered are exogenously driven, mismatches between LWR-recyclable plutonium demand and supply arise in some circumstances. The approach taken in all cases reported decreases heretofore growing MOX (or EMOX/NFF) core fractions to bring demand in line with supply. Since FSBs are not considered in this study, LWR-unrecyclable plutonium inventory, I_{SFF}, simply accumulates.

A. Base Case

1. Once-through LWR Fuel Cycle

The time dependence of plutonium inventories for the OT/LWR case is given in Fig. 3; for this case, $I_{SFF,REP,SPU} = 0$. Also shown on this figure is the time dependence of nuclear capacity, P_E. The evolution of spent-fuel age and creation distribution for this OT/LWR case is computed for use in the evaluation of the proliferation risk index.[2] Starting with the assumed initial (*ca*. 1995) history of spent fuel accumulation, the age distribution forms a growing continuum as “fresh” (radioactively “hotter”, less attractive to a potential proliferater) spent fuel is added to the older inventories; this age distribution is shown in comparision to the MOX/LWR scenario in a subsequent figure (Fig. 6). Depending on the uranium resource scenario chosen, cumulative uranium use, unit mining/mill costs, and optimal enrichment tailings composition will vary. Figure 4 gives the time dependence of accumulated uranium usage, I_U^{MM}, optimal enrichment tailings composition, x_{DU}, and uranium unit cost, UC_{MM}, for a range of resource scenarios for the OT/LWR. The uranium unit cost, UC_{MM}, forms one component of the overall fuel-cycle annual charge.[2] All fuel-cycle annual charges are converted to incremental or total costs of electricity, as well as present-value costs associated with the fuel cycle over the 100-year time frame of these computations. These costs for the OT/LWR case are shown later (Fig. 7) in comparison with other fuel cycle cases, as are the respective proliferation risk indices computed for each plutonium form/inventory. [PRI_i(ktonne yr), Fig. 11].

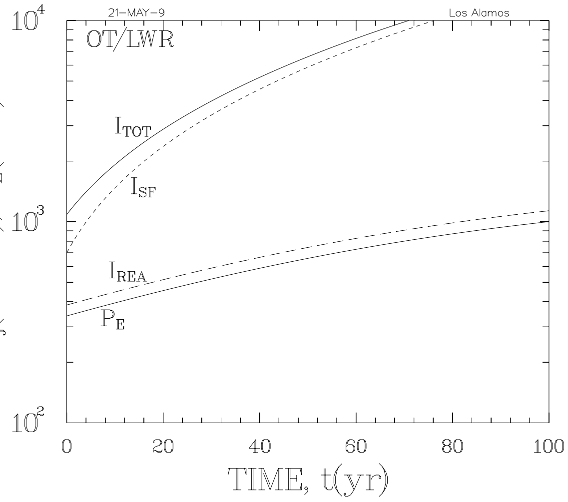

Figure 3. Time dependence of plutonium inventories for the OT/LWR case.

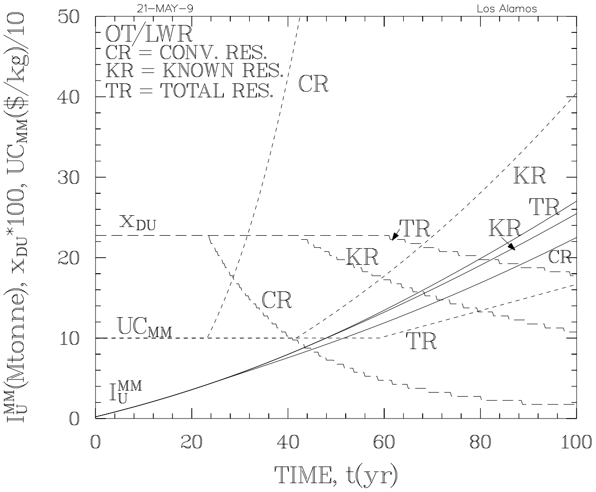

Figure 4. Cost impact of the range of uranium resource “realities” for the OT/LWR case.

2. Plutonium Recycle Base Case

Figures 5-7 give inventory, spent-fuel age, cost, and PRI impacts for the $f^f_{MOX} = 0.3$ MOX/LWR scenario based on $N_{CYC} = 4$ and KR uranium resource/cost category. Sample parametric variations away from this base case are reported in Sec. III.B. and elaborated in Ref. 2.

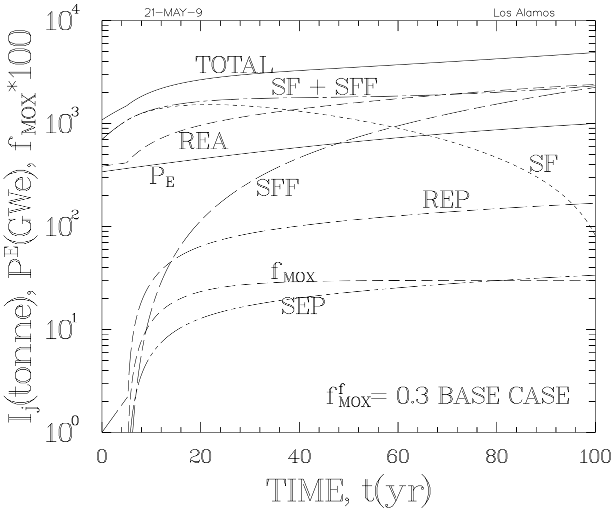

Figure 5. Time dependence of plutonium inventories for the MOX/LWR case (f^{f}_{MOX} = 0.3, NCYC = 4).

The time dependence of plutonium inventories for the base case is given in Fig. 5. The spent-fuel inventory of LWR-recyclable plutonium, I_{SF}, decreases as the inventory of LWR-unrecyclable plutonium, I_{SFF}, increases. The base case is close to an "edge" where slight increases in I_{SF} demand (*e.g.*, by increasing f^{f}_{MOX}, decreasing N_{CYC}, or implementing MOX/EMOX/NFF scenarios) will push I_{SF} inventories to zero, thereby forcing a decrease in f_j(j = MOX, EMOX, NFF) to reconcile SF-plutonium supply and demand. Figure 6 gives the evolution of spent-fuel age and creation distribution for the base case, along with comparison with the OT/LWR case. The fueling algorithm that uses the oldest spent fuel for plutonium (*e.g.*, less radioactive and more proliferation prone) depletes the older (left most part of the distribution for a given time measured at the vertical right segment of a given distribution on Fig. 6) material. The diminished and diminishing average age for the base case, τ_{SF}(MOX), compared to the OT/LWR case is also noted. These differences are reflected in the PRI computation[2].

The time evolution of the annual charges for key components of the nuclear fuel cycle for the base case, compared to the OT/LWR case, shows an increasing importance of reprocessing cost for the f^{f}_{MOX} = 0.3 MOX/LWR base case, along with a reduction in annual charges associated with uranium resource. This trade off eventually causes OT/LWR annual charges to increase above MOX/LWR annual charges at ~70 years into the computation for this KR uranium resource scenario. Generally, the use of the MOX-recycle option expectedly decreases the cumulative amount of uranium resource utilization and delays the time when uranium costs increase above a set base price and the point where concentraions in the enrichment tailings, x_{DU}, begin to decrease (Fig. 4).

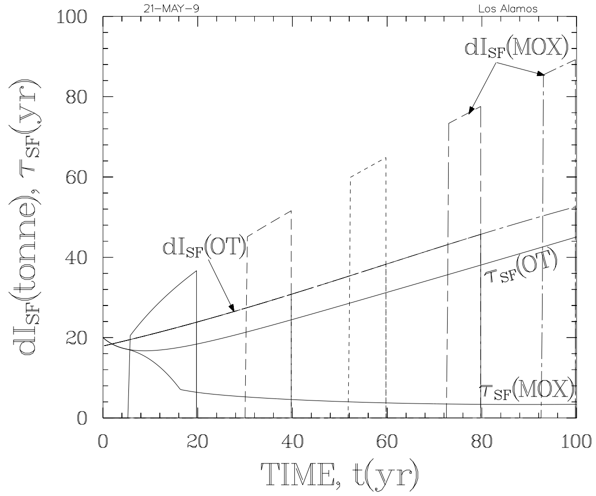

Figure 6. Evolution of spent-fuel age, τ_{SF}, and creation distribution, dI_{SF} for the MOX/LWR case, showing a comparison with the OT/LWR case. (The creation distribution at any given time starts at right and extends to the left.)

The confluence of all these effects as the fuel cycle moves from OT/LWR to MOX/LWR for a given uranium resource (cost-scaling) assumption is reflected in the Fig. 7 comparisons of COE, ΔCOE, and PV_{FC} for these two cases. All uranium resource scenarios show[2] an initial increase in COE or ΔCOE for the MOX/LWR case above that of the OT/LWR case. Depending on the uranium resource/cost assumption, these cost parameters cross at later times to give lower unit costs for the MOX options. Specifically, the CR resource case shows the MOX/LWR having lower unit costs ~35 years into the computation, with this cross-over point being pushed out to ~62 years for the KR resource category, and ≥ 100 years for the TR resource category. When differences in the present values of total fuel cycle costs between the OT and MOX options out to the 100-year computational time frame are considered, however, the MOX shows a 122 B$ benefit (11,193 $/kgPu destroyed) for the CR resource category, 87 B$ penalty (7,980 $/kgPu destroyed) for the KR resource category, and 96 B$ penalty (8,810 $/kgPu destroyed) for the TR resource category. Generally, the economic merits or demerits of MOX *versus* OT options, when expressed on a present-value basis for a given discount rate, depends strongly on costs incurred early in the evolutionary period, irrespective of unit-cost cross-overs that may occur late in a moderately discounted (0.05 $/yr) future. Furthermore, the economically preferred option depends sensitively on the description of uranium resource "reality" (*e.g.*, CR, KR, or TR).

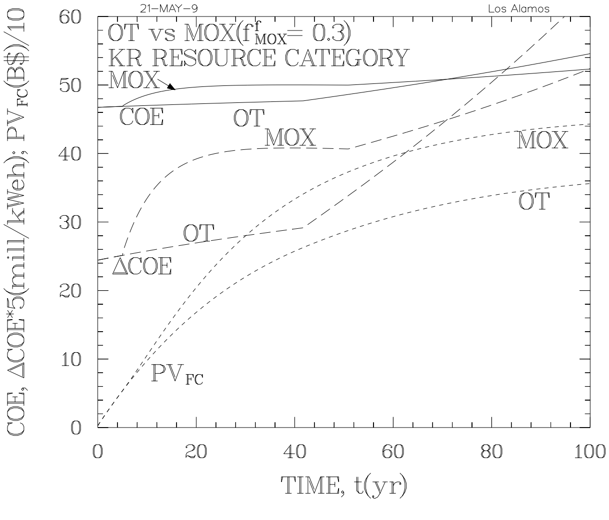

Figure 7. Time evolution of cost of electricity, COE(mill/kWeh), incremental COE related to the fuel cycle, ΔCOE(mill/kWeh), and present value of all fuel cycle charges, PV_{FC}.

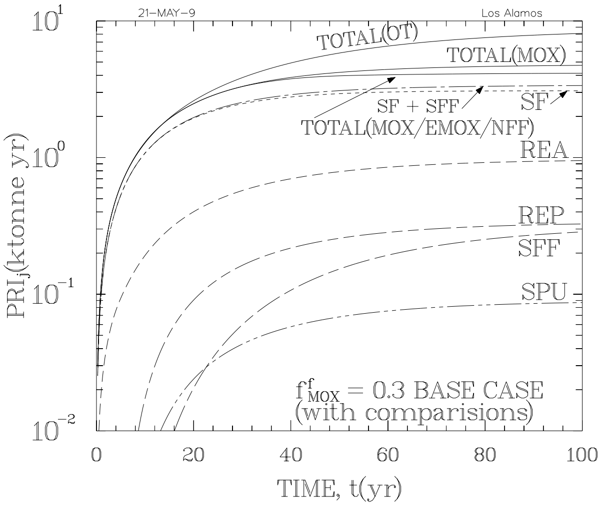

Figure 8. Time evolution of total and component proliferation risk indices, PRI(ktonne yr).

Figure 8 gives the time evolution of total and component proliferation risk indices, PRI_i(ktonne yr), for the f^f_{MOX} = 0.3 MOX/LWR case that discounts risk at a rate r = 0.05 1/yr using a pairwise weighting procedure desribed in Ref. 2. A comparison of the total PRI for the OT/LWR case, as well as for a MOX/EMOX/NFF scenario reported in Sec. III.B.4., is given. As for the OT/LWR case, plutonium in SF (recyclable to LWRs) presents the greater PRI for the weights used[2]. The transition from the OT/LWR scenario to the MOX/LWR options reduces the total PRI by a factor of ~1.7, although this model cannot translate these changes to risk reductions associated with actual consequences.

B. Base-Case Parametric Variations

The impacts of parametric variations away from the f^f_{MOX} = 0.3 MOX/LWR base case are reported in this section. These impacts are displayed in terms of the three key responses described above: plutonium inventories; costs; and PRIs. As noted above, perturbations that cause inventories of LWR-recyclable plutonium, I_{SF}, to be depleted trigger a systems response that retards the programmed increase in the core fraction, f_j(j = MOX, EMOX, NFF), to force an equilibrium between SF-plutonium supply and demand. These triggerings are reflected in subsequent inventory and cost trajectories.

1. Driver-Fuel Fission Fraction

The plutonium balances are based on a simplified neutronics model that specifies the EOL concentrations of plutonium bred into either the UOX or MOX/EMOX/NFF core regions, as well as the fraction of all energy (fissions) generated by the original driver fuel (^{235}U in UOX and BOL driver plutonium in the MOX/EMOX/NFF). These parameters are held constant for all regions and all levels of recycle. The driver-fuel fission fraction for all computations is fixed at $1 - f_{Pu} = 0.6$; 40% of the energy released and included in the burnup parameter, BU = 40 MWtd/kgHM, occurs in fissile material not originally loaded into the fuel assembly. Decreasing the fraction of the burnup derived from fissions other than those in the driver fuels increases demand on the SF-plutonium inventories to an extent that f_{MOX} for $f_{Pu} = 0.3$ must be decreased.[2] This decrease in I_{SF} is also accompanied by a corresponding decrease in the growing inventories of LWR-unrecyclable plutonium, I_{SFF}, reactor inventories, I_{REA}, and, hence, total plutonium inventories.[2] Generally, these trends are driven by the decrease in EOL driver fuel concentrations as f_{Pu} is decreased for a specified value of BU; less plutonium on average resides in the reactor and less is delivered to either SF or SFF plutonium inventories.

2. Number of MOX Recycles

The $f^f_{MOX} = 0.3$ MOX/LWR base case assumes $N_{CYC} = 4$ recycles on average are required to render recycled MOX too inefficient for use in a thermal-spectrum reactor. Reducing N_{CYC} expectedly lowers the total exposure above which plutonium is considered unusable by LWRs, increases the growth of the I_{SFF} inventories, and hastens the onset of I_{SF} inventory reduction and the need to pull back on the f_{MOX} trajectory to assure SF plutonium inventories. The total plutonium inventory, however, is only moderately impacted[2] for $N_{CYC} \geq 2$.

3. Asymptotic MOX Fraction

The demand for LWR-recyclable plutonium, I_{SF}, increases as the asymptotic value of the MOX core volume fraction, f^f_{MOX}, is increased. As this goal value of f_{MOX} is increased, however, the I_{SF} inventories are depleted, and at some point the driving function for f_{MOX} must be overridded to maintain a balance between the supply and demand of LWR-usable plutonium. This behavior is elaborated in Ref. 2, along with the impact on the average age of spent fuel in this system and the PRI. For the neutronics parameters used, asymptotic MOX fractions (again, for $\lambda_{MOX} = 0.1$ 1/yr) of 0.35 and 0.4 cause the depletion of the inventory I_{SF} and the resulting pull back on the f_{MOX} trajectory at 56 and 42 years into the MOX trajectory.

4. Transitions to Non-Fertile Fuels

The UOX → MOX → EMOX → NFF scenario depicted in Fig. 2 is examined in terms of the three assessment criteria adopted for this study: plutonium inventories; costs; and proliferation-risk indices. The removal of uranium from MOX and replacement with zirconium was assumed to increase the reactor inventories of (driver) plutonium while decreasing the rate of plutonium production in the regions of reduced fertility. For a given exogenously driven growth rate in f_j(j = MOX,EMOX,NFF), the demand on LWR-recyclable plutonium, I_{SF}, is expected to limit overall implementation of this plan to the aforementioned SF-plutonium demand-supply constraint. This behavior is depicted on Fig. 9, which compares the plutonium inventory transients for the OT/LWR (Sec. III.A.1.), MOX/LWR base case (Sec. III.A.2.), and the UOX → MOX → EMOX → NFF scenario. The comparison of costs given on Fig. 10 indicates that: a) on an (instantaneous) unit-cost basis, the UOX → MOX → EMOX → NFF scenario initially tracks the MOX/LWR (higher COEs than the

OT/LWRs), but at later times this scenario tracks the resource-driven higher COEs that characterize OT/LWRs in the out years. On a present-value basis, which is dictated largely by early histories and not by the moderately discounted future, the UOX → MOX → EMOX → NFF scenario largely follows that of the MOX/LWR base case. The former scenario destroys somewhat more (~28%) plutonium than the MOX/LWR base case; however, roughly the same PV_{FC} differential (again, relative to the OT/LWR case) is incurred, so that the unit cost of plutonium destruction for the NFF scenario is 5,860 \$/kgPu, compared to 7,980 \$/kgPu for the MOX/LWR base case.

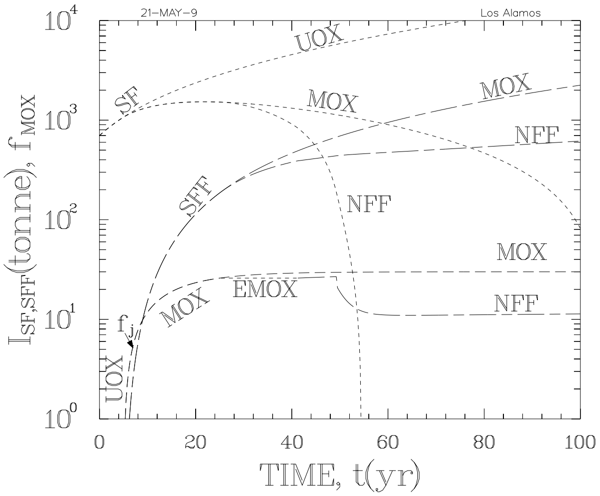

Figure 9. Time dependence of key plutonium inventories for three fuel-cycle variations depicted on Fig. 2: a) OT/LWR (designated here as UOX); b) f^f_{MOX}= 0.3 MOX/LWR (base case); and c) UOX/MOX/EMOX/NFF scenario.

Lastly, the impacts on the total PRI of the the main scenarios considered in this study are shown on Fig. 11. Relative to the OT/LWR scenario (Fig. 11, Case A), both the MOX and the NFF scenarios reduce this parameter, but the relationship between PRI and connections between actual risk and real consequences remains to be made. Generally, the NFF scenario has the lowest PRI value, but it is not much different than that for the f^f_{MOX} = 0.3 MOX/LWR base case.

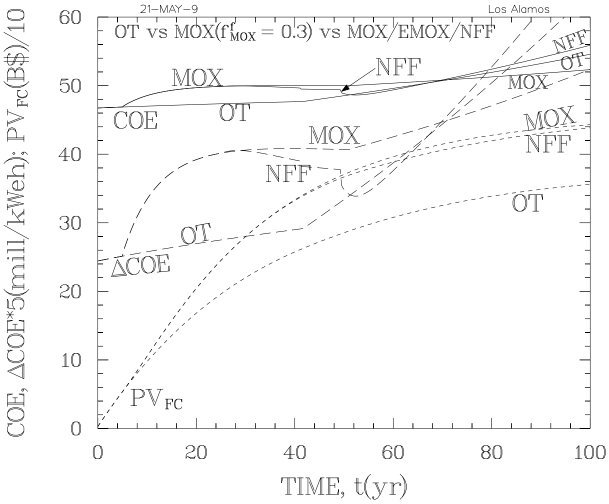

Figure 10. Time evolution of cost of electricity, COE(mill/kWeh), incremental COE related to the fuel cycle, ΔCOE(mill/kWeh), and present value of all fuel cycle charges, PV_{FC}, for: a) the OT/LWR case; b) the f^f_{MOX} = 0.3 MOX/LWR base case; and c) the UOX/MOX/EMOX/ NFF case.

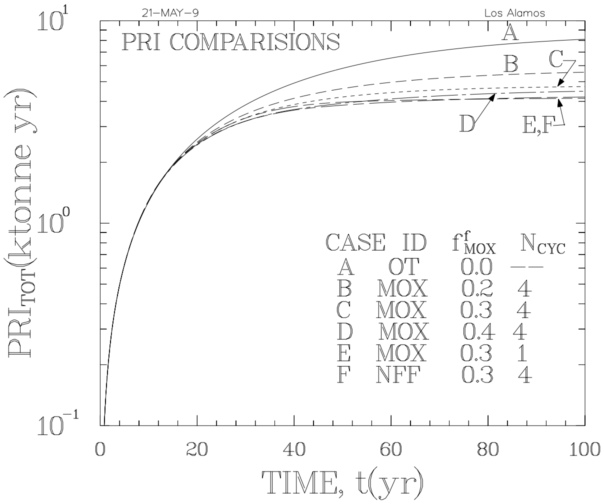

Figure 11. Time dependence of proliferation risk index for most of the key cases considered by this study.

IV. SUMMARY AND CONCLUSIONS

A simplified and highly aggregated global model has been used to evaluate interactions and trade offs between: a) plutonium inventories in four forms [*e.g.*, reactor(REA), LWR-usable spent fuel(SF), LWR-unusable spent fuel (SFF), and separated (SPU = REP + FF)]; b) fuel cycle and total energy costs; and b) a crude, inventory- and form-based, discounted measure of proliferation risk. The primary goal of these "top-level" trade studies is to stimulate more detailed study of key issues and relationships rather than to present firm conclusions and recommendations. The sensitivity of key metrics to assumed neutronics performance suggests a stronger coupling with basic core neutronics computations is needed in future studies. Also, an improved PRI metric that better assesses risk and consequences is needed. Nevertheless, key interim findings from this study are recapitulated as the following:

- The impact on cost of uranium resource depletion for the once-through LWR scenario will be felt for the Known Resources (KR) scenario[6] within ~50 years for the medium-growth scenario used throughout this investigation (340 → 1000 GWe in 100 yrs); adaptation of the CR resource scenario in these circumstances will have serious cost impacts on nuclear energy, even when ^{235}U concentrations in enrichment tailings are optimized
- A comparison of the total annual charge associated with the fuel cycle for the OT/LWR and MOX/LWR cases illustrates the increasing importance of reprocessing cost for the 30% MOX/LWR base case, with the reduction in annual charges associated with uranium resource for the MOX/LWR case eventually causing total annual fuel-cycle charges for the OT/LWR case to increase above that for MOX/LWR at ~70 years into the computation for this KR uranium resource scenario.
- Depending on the uranium resource/cost assumption, energy costs for the MOX/LWR base case fall below the OT/LWR case at later times to give lower unit energy costs for the MOX options. Specifically, the CR resource case shows the MOX/LWR having lower unit costs ~35 years into the computation, with this cross-over point being pushed out to ~62 years for the KR resource category, and ≥ 100 years for the TR resource category.
- When differences in the present values of total fuel cycle costs between the OT and MOX options out to the 100-year computational time frame (0.05 1/yr discount rate) are considered, however, the MOX shows a 122 B$ benefit (11,193 \$/kgPu destroyed) for the CR resource category, 87 B$ penalty (7,980 \$/kgPu destroyed) for the KR resource category, and 96 B$ penalty (8,810 \$/kgPu destroyed) for the TR resource category.
- Generally, the economic merits or demerits of MOX *versus* OT options, when expressed on a present-value basis for a given discount rate, depends strongly on costs incurred early in the evaluation period, irrespective of unit-cost cross-overs that may occur late in a moderately discounted future. Furthermore, the economically preferred option depends sensitively on the description of uranium resource "reality"; this dependence has been approximately, but quantitatively, shown.
- As for the OT/LWR case, plutonium in SF (LWR-recyclable) presents the greater PRI for the 30% MOX/LWR and for the weights used.[2] The transition from the OT/LWR scenario to the MOX/LWR option reduces the total PRI by a factor of ~1.7, although this model cannot translate these changes to risk reductions associated with actual consequences.
- For the simplified neutronics parameters used, the 30% MOX/LWR base case is close to an "edge" where slight increases in I_{SF} demand (*e.g.,* by increasing f^{f}_{MOX}, decreasing N_{CYC}, or implementing MOX/ EMOX/NFF scenarios for the neutronics assumptions made) will push I_{SF} inventories to zero, thereby causing a decrease in f_j(j = MOX, EMOX, NFF) to balancd SF-plutonium demand with supply.

- For the 30% MOX/LWR base case, decreasing the fraction of the burnup derived from fissions other than those in the driver fuels increases demand on the SF-plutonium (LWR-usable) inventories to an extent that f_{MOX} for $f_{Pu} = 0.3$ must be decreased. This decrease in I_{SF} is also accompanied by a corresponding decrease in the growing inventories of LWR-unrecyclable plutonium, reactor inventories, and, hence, total plutonium inventories. Generally, these trends are driven by the decrease in EOL driver fuel concentrations as f_{Pu} is decreased for a specified value of burnup, BU(MWtd/kgHM); less plutonium on average resides in the reactor and less is delivered to either SF or SFF plutonium inventories.
- Lowering the total exposure above which plutonium is considered unusable by LWRs, N_{CYC}, increases the growth of the LWR-unusable inventories, I_{SFF}, and hastens the onset of LWR-usable inventory (I_{SF}) reduction and the need to pull back on the f_{MOX} trajectory to assure SF plutonium inventories; the total plutonium inventory, however, is only moderately impacted for $N_{CYC} \geq 2$.
- The removal of uranium from MOX and replacement by zirconium, for the neutronics assumptions made, both increases the reactor inventories of (driver) plutonium while decreasing the rate of plutonium production in the regions of reduced fertility. On an (instantaneous) unit-cost basis, the UOX → MOX → EMOX → NFF scenario initially tracks the MOX/LWR (higher COEs than the OT/LWRs), but at later times this scenario tracks the resource-driven higher COEs that characterizes OT/LWRs in the out years. On a present-value basis, the UOX → MOX → EMOX → NFF scenario largely follows that of the MOX/LWR base case. The former scenario destroys somewhat more (~28%) plutonium than the MOX/LWR base case, however, at roughly the same PV_{FC} differential (again, relative to the OT/LWR case), so that the unit cost of plutonium destruction for the NFF scenario is 5,860 \$/kgPu, compared to 7,980 \$/kgPu for the 30% MOX/LWR base case.
- Relative to the OT/LWR scenario, both the MOX and the NFF scenarios reduce the PRI parameter, but the connection between PRI and actual risk and real consequences remains to be made. Generally, the NFF scenario has the lowest PRI value, but it is not much different than that for the 30% MOX/LWR base case.

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NOMENCLATURE

B	plutonium "burner" (FSB)
BOL	beginning of life
BU(MWtd/kgHM)	burnup
COE(mill/kWeh)	cost of electricity
CR	conventional resource category[6]
DB,DP	"burner", "producer" demand
dI_{SF}(kgPu)	spent-fuel creation distribution
EOL	end of life
EMOX	evolutionary MOX (MOX + NFF)
FF	fuel fabrication
FPD	full-power day
FSB	fast spectrum burner
f_i	core fraction of i^{th} fuel form
f_{MOX}^{f}	asymptotic MOX core fraction
f_{Pu}	fissions other than in driver fuel
HM	heavy metal (U,Pu)
I_j(kg)	plutonium inventory in i^{th} form
I_U^{MM}(Mtonne)	cumulative uranium ore mined
KR	known (uranium) resource category[6]
MM	mining and milling
MOX	mixed (Pu,U) oxide fuel
N_{CYC}	number of LWR recycles
NFF	nonfertile fuel
OT	once-through LWR fuel cycle
P	plutonium "producer" (LWR)
P_E(MWe)	net-electric capacity, $P_B + P_P$
$P_{B,P}$(MWe)	"burner", "producer" capacity
$\dot{P}_{B,P}$(MWe / yr)	introduction rate
PD(MWt/m^3)	average core power density
PRI_j(ktonne yr)	proliferation risk index of j^{th} form
$PV_{FC}(\mathrm{B\$})$	present-value fuel-cycle charge
$p_f^{B,P}$	plant availability
R_i(kgPu/yr)	mass flow rate in i^{th} stream
REA	reactor plutonium inventory
RP	plutonium in reprocessing
r(1/yr)	discount rate
r_B(kgPu/yr/MWe)	normalized burnup rate
r_P(kgPu/yr/MWe)	normalized production rate
SF	recyclable plutonium in spent fuel
SFF	unrecyclable plutonium in spent fuel
SI(kgHM/MWt)	specific inventory
SP(MWt/kgHM)	specific power
SPU	separated plutonium
TR	total (uranium) resource category[6]
UOX	uranium oxide fuel
x_j	concentration
ΔCOE(mill/kWeh)	incremental COE for fuel cycle
$\eta_{TH}^{B,P}$	thermal-conversion efficiency
λ_{MOX}(1/yr)	rate of MOX implementation
τ_j(yr)	time constant for j^{th} process
τ_{SF}(yr)	average age of spent fuel