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

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## ABSTRACT

The potential for reducing plutonium inventories in the civilian nuclear fuel cycle through recycle in LWRs of a variety of mixed-oxide forms is examined by means of a cost-based plutonium-flow systems model. This model emphasizes: a) the minimization of separated plutonium; b) the long-term reduction of spent-fuel plutonium; c) the optimum utilization of uranium resources; and d) the reduction of (relative) proliferation risks. This parametric systems study utilizes a globally aggregated, long-term (~100 years) nuclear-energy model that interprets scenario consequences in terms of material inventories, energy costs, and relative proliferation risks associated with the civilian fuel cycle. The impact of introducing nonfertile fuels (NFF, *e.g.*, plutonium oxide in an oxide matrix that contains no uranium) into conventional (LWR) reactors to reduce net plutonium generation, to increase plutonium burnup, and to reduce exo-reactor plutonium inventories also is examined.

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# I. INTRODUCTION

## A. Background

Nuclear energy worldwide is at a crossroads. Key determinants of policies that are shaping the future of nuclear energy are[1]: a) economic (capital, operational and maintenance, including: b) fuel and fuel-cycle costs, availability); c) technological (safety, size); d) political (fuel and technological resource availability, e) resource and energy security, nuclear proliferation); f) environmental (minimization and security of long-term waste, sustainability with respect to future generations, conflicting goals); g) and social (regulation, technical, and financial infrastructures and organizations). Threading these key elements that impact nuclear policies is the plutonium issue.

The "tension" between nuclear-weapons and nuclear-energy uses of plutonium has generated a deeply divided and evolving debate over the growing commercial (spent fuel) and excess weapons inventories of this material[2]. The debate over the best way of dealing with the plutonium issue has centered primarily on reprocessing of spent fuel. Over the years, rationale for reprocessing and plutonium recycle has moved[3] from: a) primarily economic and energy-security arenas (up to the mid-1970s); b) to less-strategic justifications based on improved management of radioactive wastes (up to the mid-1980s); c) to the present stance centered on interim-storage *versus* direct-disposal options that are based primarily on long-term environmental and (once again) energy-security considerations. Arguments against closing the nuclear fuel cycle through reprocessing are based largely on fears of an exponential increase in proliferation potential as world inventories of civilian plutonium grow. Furthermore, this situation is driven by operations and processes that may not become economic for decades to come[4]. Current arguments supportive of plutonium recycle most recently[8] have focused primarily on non-economic issues based on rationale that center on the: a) environmental (reduced bio-toxicity of disposed wastes); b) resource (uranium conservation through recycle of both uranium and plutonium in LWRs); c) strategic (energy independence and option flexibility, particularly for nations without large resource endowments); d) political (proliferation risks can be reduced by reprocessing scenarios that minimize accessible inventories of separated plutonium); and e) risk-minimizing (technology footing of reprocessing is firmer than direct disposal).

Among the elements contributing to the complexity of the reprocessing/recycle debate are: a) the long-term ("plutonium mine") *versus* short-term (spent-fuel *versus* separated/stockpiled plutonium forms) nature of the proliferation risk; b) regionalization of growths in population and associated energy demand, as well as how that demand will be met; c) globalization of energy supply and environmental impacts; and d) relationships between security of energy supply, economic well being, and regional propensities for nuclear proliferation. A recent IAEA symposium[6] focused on the "new realities" arising from these elements and the related impacts on nuclear reactor and fuel-cycle strategies. Specifically, these new realities are translated into concrete terms, as follows:

- Nuclear energy growth (344 GWe in 1996, at most 380 GWe by 2000) had fallen far short of earlier projections (850-1200 GWe by 2000, as projected in the 1980s); uranium supplies will consequently last longer;
- Nuclear energy demand seems to be shifting to Asia, with growth in most OECD countries flattening;
- Fast-spectrum reactors are not yet developed or deployed into a commercial reality;
- The closed fuel cycle has not taken hold;

- Reductions have occurred in U.S. and Russian nuclear arsenals, along with the release of weapons plutonium, possibly to the civil nuclear fuel cycle; the hard boundary between military and civil nuclear enterprises is softening;

- Eastern Europe has a strong commitment to nuclear energy, but the backend of the fuel cycle does not exist, and little spent fuel storage is available;

- Inventories of separated plutonium and spent fuel are growning, with potential regional solutions to the fuel cycle being implemented;

- Reasonably assured uranium resources were 2.5 Mtonne at a cost of 130 \$/kgU in 1988, but the present reality is uranium costs of 18 \$/kgU with the prospects of substantial finds if this price drifts upward; this resource/price relationship is driving regional decisions to reprocess spent commercial fuel or not;

- World inventories of separated commercial plutonium is 166 tonne (1996), is expected to decrease to 140 tonne by the year 2000, while at least 50 tonnes of weapons plutonium will be released to the commercial sector.

- Over 100 ktonne of commercial spent fuel will be accumulated worldwide by the year 2000, with ~40% (~390 tonne plutonium) of this inventory possibly being reprocessed;

- The view on the value of plutonium is split: a) no economic value (maybe negative) and should be disposed; b) a valuable fuel resource for future generations;

- Plutonium has been "demonized" by the public because of risks associated with nuclear weapons proliferation and with accidental releases.

That recognition of and/or approaches to these "new realities" vary greatly around the world is reflected in the 4-5 positions that have developed with respect to the theme of the Ref.-6 symposium: a) no reprocessing in the U.S.; b) reprocessing and plutonium recycle in France; c) reprocessing and plutonium accumulation for anyone in the U.K.; d) processing, plutonium storage, and development of fast reactors and recycling thermal reactors in Japan; and e) evolution of the thorium cycle through fast reactors in India.

B. Approach

No single analysis or approach can address the complexity of the issues identified above, particularly when consideration is given to drivers that are external to nuclear energy[7]. Plutonium management, however, is a strong and common linkage between many of these complex issues. This scoping study addresses in broad economic and proliferation terms one approach to managing better plutonium in the civilian fuel cycle. Specifically, consideration is given to the use of plutonium recycle in thermal-spectrum reactors in the forms of 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[8]) in combination with advanced (inventory-minimizing) reprocessing schemes. The combined use of MOX and NFF in transitioning from the former to the latter is also considered (*e.g.*, evolutionary mixed oxides, EMOX). This direct, albeit short-term, approach, offers a degree of freedom/flexibility that can address some of the above-listed issues by: a) reducing the plutonium being generated in conventional reactors; b) providing a more effective means to transform plutonium presently being released from dismantled nuclear weapons; c) reducing inventories of plutonium residing in spent fuel and the future proliferation risks related thereto; and d) lowering plutonium inventories in closed fuel cycles of the future needed for nuclear energy to enter a truly sustainable regime characterized by low inventories of "idle" plutonium (*e.g.*, either in spent-fuel or inventoried in separated forms).

A three-pronged approach to assessing the merits and limitations of MOX $\rightarrow$ EMOX $\rightarrow$ NFF utilization in thermal reactors is being pursued at Los Alamos[8]: a) reactor-core physics analyses of NFF utilization in existing (LWR) reactors, including safety (stability, temperature coefficients of reactivity, power peaking, *etc*.) and fuel economics (neutron economies based on 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). Early progress in the latter area is reported herein.

Using aggregated reactor-core parameters guided by computations from detailed neutronic models, these systems studies are based on a dynamic model of global plutonium flow that is driven by a range of nuclear-energy growth scenarios[1,7,9,10]. This simplified, but transparent and parametrically flexible, continuum (*versus* discrete-event) model has been compared to a more exact dynamic, mixed fuel-cycle model[11]. The fractions of NFF and MOX fuel forms in the LWR core, and related integral core parameters (*e.g.*, respective fuel fractions, specific powers or inventories, *etc*.) are varied in anticipation of results from the detailed reactor-core neutronic and burnup computations[8,11]. 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 and 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. Preliminary estimates of relative inventory (both magnitude and form), economic, and proliferation-risk impacts are reported. Although the model describe in the following section includes options that utilized plutonium, particularly the SFF forms, in fast-spectrum burners (FSBs, *e.g.*, LMRs or accelerator-driven systems), only results base on conventional LWRs are reported here.

## II. MODEL

### A. Overview

The plutonium flow and inventory model used to make preliminary assessments of advanced nuclear fuels and associated fuel cycles examines a globally aggregated nuclear economy out to a ~100-year time horizon. The growth of this aggregate nuclear capacity, $P_E$, is exogenously input according to $P_E(t)/P_E(0) = g(t)$; the following logistics equation is used to describe g(t):

$$g(t) = \frac{a}{1 + (a - 1)e^{\lambda_P t}} , \tag{1}$$

where $a = P_E(\infty)/P_E(0)$; the parameters a and $\lambda_P$ are chosen to fit specific scenarios created by more detailed models[9,10,12,13]; the logarithmic growth rate associated with Eq. (1) is $d\ln P_E/dt = \lambda_P/[1 + e^{\lambda_P t}/(a - 1)]$. This model approximates the aggregated nuclear world and associated plutonium flows and inventories using a single differential equation to describe the plutonium inventory in the two spent-fuel forms, $I_{SF}$ and $I_{SFF}$(kg), along with material residence times, $\tau_j$(yr), at key points in the global nuclear fuel cycle [*e.g.*, j = REP (reprocessing); j = SPU (separated plutonium awaiting allocation to specific reactor; and j = REA (reactors)]. The two spent fuel forms identified above correspond to LWR-recyclable (SF) and LWR-unrecyclable (SFF), depending on the number of LWR recycles, $N_{CYC}$, experienced.

The continuous (*versus* discrete event[11]) analysis, along with the use of exogenous residence times, present modeling limitations that are balanced by a level of transparency and simplification that allows a direct assessment of economic and (uranium) resource implications of a range of advanced fuel and fuel cycle scenarios. In its general form, the model tracks plutonium inventories in a global system comprised of a (plutonium) "producer" and a plutonium "burner". This two-component model is depicted in Fig. 1, which indicates that the "producer" is characterized by a thermal-spectrum Light-Water Reactor (LWR), and the "burner" is a fast-spectrum Liquid-Metal Reactor (LMR) having both breeding and integral-processing (closely coupled) capability. The "burner" could also be an accelerator-driven subcritical system designed primarily as an actinide burner and (longer-lived) fission-product transmuter[14,15]; for the purposes of this study, this system is referred as a fast-spectrum burner (FSB). The ratio of net-electrical power generated from each system, $\rho = P_P(LWR)/P_B(FSB)$, is determined exogenously (and parametrically) as a function of time; a more exacting approach would determine $\rho$ on the basis of market/economic considerations[10,12,13].

The results presented herein focus on understanding tradeoffs related to a range of LWR operating scenarios [*e.g.*, the fraction of LWRs in the system, $f_{LWR} = \rho/(1 + \rho)$, is unity]. These operating conditions are defined primarily by the fraction of the (LWR) core that uses recycled plutonium, $f_i$ (*e.g.*, in this case the "producer" functions as, but in the context of this study is not considered, a "burner"), and how that (volume) fraction of the (LWR) core that is not conventional uranium oxide (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 are elaborated in the following section

B. LWR Core Segmentation/Composition

As is indicated in Fig. 2, the LWR core in the most general case has a MOX volume fraction $f_{MOX}$, an EMOX volume fraction $f_{EMOX}$, and a non-fertile fuel volume fraction $f_{NFF}$; the remaining fraction $1 - f_{TOT}$ is a conventional uranium oxide (UOX) compositions, where $f_{TOT} = f_{MOX} + f_{EMOX} + f_{NFF}$. The EMOX part of the non-UOX segment of the core can be composed by mixing a fraction $f^*_{MOX}$ of the MOX segment with a fraction $f^*_{NFF}$ of the NFF segment. The basic building blocks of the evolving EMOX core segment are the MOX and NFF segments, each being characterized by their respective densities, $\rho_j$, specific powers, $SP_j$(MWt/kgj), and either full-power-days of exposure, $FPD_j$(d), or burnup, BU(MWtd/kgj) = $SP_j$ $FPD_j$. Specific inventory is defined as $SI_j = 1/SP_j$, and regional power density is given by $PD_j(\mathrm{MWt/m^3}) = BU_j\ \rho_j/FPD_j$. Similar parameters are identified for the UOX core sector. For the purposes of these computations, both $FPD_j$ and $PD_j$ are chosen as independent of core region, with $BU_j$, $SP_j$, and/or $SI_j$ tracking the corresponding core region densities; these densities incorporate an averaging of the local coolant volume fraction, $f_{COOL}$.

Any number of scenarios can be envisaged to describe the evolution of core segmentation and compositions depicted in Fig. 2.  Based both on neutronic and materials considerations, the evolutionary model illustrated in Fig. 3 was adopted to project the time dependence of the respective core volume fractions and compositions. This model suggests a time $\tau_{MOX}$ at which conventional UOX cores begin to introduce MOX fuel, with the core volume fraction $f_{TOT} = f_{MOX}$ increasing according to a prescribed function up to a time $\tau_{EMOX}$. At this point, $f_{TOT} = f_{EMOX}$ is held constant as the fraction of the non-fertile component (*e.g.*, zirconium) relative to (depleted) uranium, $\zeta = x_{Zr}/(x_{Zr} + x_U)$, is increased. When $\zeta$, which is also increased according to a prescribed function of time, reaches a predesignated value, $\zeta_c$, all uranium is removed from the EMOX part of the core, that core segment is reclassified as NFF, and the respective core volume fraction, $f_{TOT} = f_{NFF}$, again is increased according to yet another prescribed function of time. Hence, the following sequential four phases are envisaged by the model: UOX $\rightarrow$ MOX $\rightarrow$ EMOX $\rightarrow$ NFF, with the compositions and core volume fractions varying according to exogenously determined functions of time, as is indicated in Fig. 3. With this UOX $\rightarrow$ MOX $\rightarrow$ EMOX $\rightarrow$ NFF evolutionary scenario defined, the plutonium inventory accumulations in spent fuel, $I_{SF}$(kg), reprocessing, $I_{REP}$(kg), storage separated plutonium, $I_{SPU}$(kg), and that contained in operating reactors, $I^{P,B}_{REA}$(kg), are determined from the simplified, aggregated mass balance described in the following section.

C.  Aggregated Mass Balance

Four rates of plutonium flow, $R_j$(kg/yr), are associated with the model depicted in Fig. 1: plutonium production delivered to spent-fuel storage, $R_P$; plutonium taken (as is needed) from spent-fuel storage and delivered to reprocessing, $R_{SF}$; plutonium moving from reprocessing for interim storage as separated material, $R_{REP}$; and plutonium taken from interim storage to meet a composite demand presented by producer (LWR) and burner (FSB) systems, $R_D$.

In cases where the FSB (LMR or ATW) is considered, closely coupled (integral) processing of plutonium is assumed, with the burner representing only a plutonium demand; the "burner" introduces no net plutonium to the system being modeled, as is indicated diagrammatically in Fig. 1. Hence, for the purposes of this analysis, plutonium is produced only in the LWR of a given core configuration, and, within the constraints of the simple continuum model used here, is described by

$$R_P(\mathrm{kgPu/yr}) \;=\; r_p\ p^{fP}\ P_P\left[(1-\ f_{TOT})+\ f_{TOT}\frac{x_U}{1-\ x_{Pu}^{UOX}}\ \ \frac{<\rho>}{\rho_{UOX}}\right]$$

$$+\ r_p\ p_{fP}\ \ P_P\ \ f_{TOT}\ \frac{<\rho>}{\rho_{UOX}}\ \ \frac{x_{Pu}\ -\ \Delta x_{Pu}}{x_{Pu}^{UOX}}\ \ , \qquad (2)$$

where $r_p$(kgPu/MWe/yr) = DPY $x_{Pu}^{UOX}$ /($BU_P^{UOX}$ $\eta_{TH}^{P}$) (= 0.2808 for $x_{Pu}^{UOX}$ = 0.01, $BU_P^{UOX}$ = 40 MWtd/kgHM and $\eta_{TH}^{P}$ = 0.325) is a normalized plutonium production rate from the UOX part of the LWR core. Plutonium production in the $f_{TOT}$ fraction of the core is linearly corrected for diminishing uranium content as the scenario enters the EMOX and NFF phases, as well as any density differences arising. The last term in Eq. (2) represents that part of the original plutonium loading not fissioned, where

$$\Delta x_{Pu}\ =\ x_{Pu}^{UOX}\ \frac{r_b}{r_p}\ \ \frac{\rho_{UOX}}{<\rho>}\left[1-\ f_{Pu}\frac{x_U}{x_{Pu}^{UOX}}\right]\ . \qquad (3)$$

Hence, the burnup fraction of the original plutonium loading is approximated as $f_B^{Pu}$ = $(x_{Pu}\ -\ \Delta x_{Pu})/x_{Pu}$, where the normalized burnup rate is $r_b$(kgPu/MWe/yr) = SPY ($A_F$/1000)/($E_F$ e $N_A$ $\eta_{TH}^{P}$) (= 1.2004 for $\eta_{TH}^{P}$ = 0.325, corresponding to $\alpha$ = 0.3901 kgPu/MWt/yr), and the $f_{Pu}$ term accounts for energy generated by fissions not occurring in the original (driver) fissile-fuel loading; this fraction is assumed to decrease linearly with decreases in the (depleted, natural) uranium content.

Plutonium is held in the spent-fuel form until a demand arises for use in either the "producer/burner" LWR or the (sub-breeding) FSB (LMR or ATW). This demand, again in the context of the continuum model used here, is given by

$$R_D(\mathrm{kgPu/yr})\ =\ r_p\ \ p_{fP}\ \ P_P\ \ f_{TOT}\frac{<\rho>}{\rho_{UOX}}\ \ \frac{x_{Pu}}{x_{Pu}^{UOX}}+\ SI_{Pu}\frac{dP_P}{dt}$$

$$+\ r_b'\ \ p_{fB}\ \ P_B(1-\ BR)+\ SI_B\frac{dP_B}{dt}\ \ . \qquad (4)$$

The rate of change of plutonium contained in spent fuel is given by the difference in the production and demand rates, as modified by the dynamics of the interim reprocessing (REP) and separated-plutonium storage (SPU). These interim dynamics (Fig. 1) are modeled by the respective "holdup" times, $\tau_{RP}$ and $\tau_{SPU}$. Hence, the plutonium inventoried in (LWR-usable) spent fuel is given by

$$\frac{dI_{SF}}{dt}(\mathrm{kgPu/yr}) = R_P(1 - 1/N_{CYC}) - R_D - (R_{SF} - R_D) \quad , \tag{5}$$

where $N_{CYC}$ is the average number of LWR cycles after which the plutonium is considered LWR-unusable; the fraction $1/N_{CYC}$ of $R_P$ is added to the $I_{SFF}$ inventory for eventual use in the FSBs.

Since the time dependencies of $R_P$ and $R_D$ are driven exogenously primarily by $P_P$, $P_B$ (through $P_E = P_P + P_B$ in Eq. (1), $\rho(t)$, $f_{TOT}$, and the evolution of the various core compositions and (other) nuclear parameters), Eq. (5) is readily solved for $I_{SF}$, once $R_{SF}$ is determined. Since $dI_{RP}/dt - R_{SF} - R_{RP}$ and $dI_{SPU}/dt = R_{RP} - R_D$, and specifying $I_{SPU} = \tau_{SPU} R_D$, the following expression gives the rate at which plutonium must be withdrawn from the spent-fuel storage:

$$R_{SF}(\mathrm{kg/yr}) = R_D + (\tau_{SPU} + \tau_{RP}) \frac{dR_D}{dt} + \tau_{RP}\ \tau_{SPU} \frac{d^2 R_D}{dt^2} \quad . \tag{6}$$

The derivatives in Eq. (6) are either numerically or analytically determined for use in the numerical solution for $I_{SF}$ [Eq. (5)]. The reprocessing and separated plutonium inventories are $I_{RP} = \tau_{RP}(R_D + \tau_{SPU}\, d^2R_D/dt^2]$ and $I_{SPU} = \tau_{SPU} R_D$, respectively. The amount of plutonium stored as actively fissioning material in reactors is approximated by the following expression:

$$I_{REA}(\mathrm{kg}) = P_P\ (SI^{j}_{Pu} + SI^{UOX}_{Pu}) + P_B\ SI_B\ x^{B}_{Pu} \quad , \tag{7}$$

where $SI^{j}_{Pu}$(kgPu/MWe) is the specific inventory of plutonium in the j = MOX,EMOX,NFF region of the "producer/burner", $SI^{UOX}_{Pu}$ (kgPu/MWe) is the nominal plutonium specific inventory in the UOX region of the "producer/burner", and $SI_B$(kgHM/MWe) is the specific inventory in the FSB having nominal plutonium concentration $x^{B}_{Pu}$. The shortcoming of this continuum analysis is the inexactness in selecting these "nominal" plutonium concentrations. Typically, $SI^{UOX}_{Pu}$ and $x^{B}_{Pu}$ are taken as average values throughout a given burn cycle, and $SI^{j}_{Pu} = f_{TOT} <\rho> <x_{Pu}>/(PD_j\ \eta^{P}_{TH})$, where $<x_{Pu}>$ is an average between $x_{Pu}$ (initial plutonium concentration) and $x_{Pu} - \Delta x_{Pu}$ (final plutonium concentration).

The parameters needed to evaluate the material balance described above are entered as exogenous input. Table I list typical input values used in this study.

D. Proliferation Risk

A proliferation risk is associated with the five plutonium streams being considered [*e.g.*, reactor, two spent-fuel forms, reprocessing, and (separated-plutonium) storage]. Whereas inventory/aspiration-driven methods for assessing related risks associated with the civilian fuel cycle have been suggested[16,17] and evaluated[18], the present analysis adopts a simplified method based on a time-discounted integral of "risk exposures", $EXP_j$, for each of the j points of plutonium accumulation (*e.g.*, j = REA, SF, SFF, SPU, REP) to form an *ad hoc* proliferation risk index, $PRI_j$, as follows:

$$EXP_j(\text{ktonne yr}) = \int_0^t \frac{I_j \ dt/10^6}{(1 + r)^t} \ , \tag{8A}$$

$$PRI_j(\text{ktonne yr}) = w_j \ EXP_j \ , \tag{8B}$$

$$PRI = \sum_j PRI_j \ , \tag{8C}$$

In these expressions, r(1/yr) is a factor that accounts for future (*e.g.*, technological) improvements that might reduce proliferation risk, and Saaty's pairwise judgment methods[17-19] are used to assess the relative importance or weights of each plutonium stream/inventory in contributing to the overall risk of proliferation from the civilian fuel cycle. On a scale from 1 to 9, the relative importance of the Saaty pairwise matrix, $a_{ij} = w_i/w_j$, used in this analysis is shown in Table II. For the purposes of the PRI evaluations, the two spent-fuel forms, SF (LWR-recyclable) and SFF(LWR-unrecyclable) are combined into a single spent-fuel entity; essentially, no plutonium “isotopics credits” are taken for the highly recycled material. Also, proliferation risk is assumed to be proportional only to total inventory, irrespective of the inventory levels at a given site or the dispersion of such sites; risk may saturate at high inventories, and many sites with reduced inventory may present a greater risk of theft that fewer sites having higher inventories.

As is indicated on Table II, the relative importance and weight of spent fuel in contributing to proliferation risk is expected to depend on the (post-REA) “age” of the spent-fuel inventory, $\tau_{SF}$(yr), with the relative importance, $a_{ij}$, increasing as the $\tau_{SF}$ increases. To account for this increased attractiveness of plutonium in older spent-fuel, the element $a_{REA,SF}$ in the Saaty pairwise matrix is given the following age dependence:

$$a_{REA,SF}(\tau_{SF}) = (a^o_{REA,SF} - a^f_{REA,SF}) \ e^{-\lambda_{AGE}\tau_{AGE}} + a^f_{REA,SF} \ , \tag{9}$$

where the low-age (fresh, highly radioactive) and high-age (old, reduced radioactivity) values of $a_{REA,SF}$ are listed in the Table-II footnote. Depending on the rate r at which risk is discounted, the increasing attractiveness of old spent fuel (to the proliferater) is partly negated by the discounting process. After computing the time-dependence of $\tau_{SF}$ for a given fuel-cycle scenario, the pairwise-comparison element $a_{REA,SF}$ is computed, the other elements $a_{SF,j}$ are adjusted to be self-consistent with the other elements $a_{ij}$ (i,j ≠ SF), and the Saaty matrix (Table II) resolve for a new set of weights, $w_j$, constrained to assure $\sum_j w_j = 1.0$.

## E. Costing

### 1. Annual Charges and Cost of Electricity

The essential elements of the nuclear fuel cycle depicted schematically in Fig. 4 are subjected to a top-level cost estimate based on a procedure described in Ref. 20 and developed for implementation in a multi-region global energy model[9,10,21]. Using highly aggregated unit costs, $UC_j$, as described in Table I for the $j^{th}$ system or process, incremental costs associated with the fuel cycle are expressed either as an annual charge, $AC_j$(\$/yr), or as an incremental cost of electricity, $\Delta COE$(mill/kWeh). The following items are accounted in estimating the incremental fuel- cycle cost:

- uranium mining and milling, $AC_{MM}$(\$/yr);
- uranium conversion ($U_3O_8$) to $UF_6$), $AC_{CV}$(\$/yr);
- uranium enrichment, $AC_{ER}$(\$/yr);
- fuel fabrication, $AC_{FF}$(\$/yr);
- spent fuel, $AC_{SF}$(\$/yr);
  - transport, $AC_{SF}^{TR}$(\$/yr);
  - storage, $AC_{SF}^{ST}$ (\$/yr);
- reprocessing, $AC_{RP}$(\$/yr);
- fission-product storage, $AC_{FP}$(\$/yr).

In some cases, these unit costs will vary, depending on whether the system being considered pertains to a "producer" (LWR) or a "burner" (FSB).

Generally, multiplication of the respective material or power flow, $R_j$ or $P_j$, with the respective unit cost, $UC_j$, listed in Table I gives the corresponding fuel-cycle-related annual charge; at the present level of analyses, life-cycle costs are not computed. Summation of these j annual charges for each of i (= LWR,FSB) reactor types, $AC = \sum_{i,j} AC_j^i$, and dividing by the respective annual energy generation gives the following expression for fuel-cycle related energy costs, $\Delta COE$:

$$\Delta COE = \frac{AC}{HPY \; \langle p_f \rangle \; P_E} \; , \tag{10}$$

where the average plant availability is $\langle p_f \rangle = f_{LWR}\, p_f^P + (1 - f_{LWR})\, p_f^B$, and $f_{LWR} = \rho/(1 + \rho)$. For all cases reported herein, $\rho$ is set to a large value and $f_{LWR} = 1.0$. If the unit total cost of reactor type i is $UTC_i$(\$/We), the fixed charge rate applied to the $i^{th}$ reactor type is $FCR_i$(1/yr), and the annual operating cost of the $i^{th}$ reactor type as a fraction of the total plant investment is $f_{OP}^i$(1/yr), then the total cost of electricity can be estimated from the following expression:

$$\mathrm{COE(mill/kWeh)} = \frac{f_{LWR}(FCR_{LWR} + f_{OP}^{LWR})UTC_{LWR} + (1 - f_{LWR})(FCR_{FSB} + f_{OP}^{FSB})URC_{FSB}}{HPY \ <p_f> \ P_E/10^6}$$

$$+ \ \Delta COE \ . \tag{11}$$

Both COE and ΔCOE are monitored as a function of time for each fuel-cycle scenario considered (Fig. 3), with Table I listing key unit cost, financial, and operational parameter for both reactor types considered.

2. Uranium Resource

An essential element of the fuel-cycle cost is the cost of uranium, as expressed by $UC_{MM} = U_1 \ M_U^{\nu}$, where $M_U$(MtonneU) is the accumulated uranium utilization, and the fitting constants $U_1$ and $\nu$ depend on the uranium resource category. Based on forecasts of uranium resources *versus* unit cost given in Ref. 22, as interpreted by Ref. 23, Fig. 5A illustrates the uranium cost *versus* resource amount for a range of resource categories. The cost *versus* resource for Conventional (CR), Known (KR), and Total (TR) Resources is shown in Fig. 5B, along with corresponding curve fits used in this study. Uranium in seawater is not included in these resources, which at 5% amounts to ~18 × TR for the highest-cost category reported (800 \$/kgU)[23].

3. Uranium Enrichment

For a given $^{235}$U concentration, x, the separation potential is[24,25] $\phi(x) = (2x - 1)\ln(x/(1-x))$, and the separative work required per unit amount of enriched uranium is given by

$$SWU = \phi(x_{EU}) - \phi(x_{DU}) - \frac{x_{ER} - x_{DU}}{x_{NU} - x_{DU}}[\phi(x_{NU}) - \phi(x_{DU})] \ , \tag{12}$$

where for $^{235}$U concentration $x_j$, NU = natural uranium, EU = enriched uranium, and DU = depleted uranium (tailings). If the unit costs of natural uranium fed to the enrichment process is $(UC_{MM} + UC_{CV})$ (\$/kgU), and that of the enrichment energy is $UC_{ER}$ (\$/kg SWU), the unit cost of enriched uranium is given by[24,25]

$$UC_{EU}(\$/kgU) = \frac{x_{ER} - x_{DU}}{x_{NU} - x_{DU}}(UC_{MM} + UC_{CV}) + SWU \ UC_{ER} \tag{13}$$

This expression minimizes at a tailings concentration, $x_{DU}^{MIN}$, given by

$$\frac{[(UC_{MM} + UC_{CV})/UC_{ER} + \phi(x_{NU})]}{1 - 2x_{NU}} = \frac{\phi(x_{DU}^{MIN})}{1 - 2x_{DU}^{MIN}} + \frac{(x_{NU} - x_{DU}^{MIN})(1 - 2x_{DU}^{MIN})}{x_{DU}^{MIN}(1 - x_{DU}^{MIN})(1 - 2x_{NU})} \ . \tag{14}$$

## III. RESULTS

An organization of cases examined is given in Table III. The main fuel-cycle scenarios consider are once-through (OT) LWRs, plutonium recycle (MOX) in LWRs, and an evolution through EMOX to cores operated with some fraction of NFF. The key exogenous variables are: a) resource grade (CR, KR, or TR, Fig. 5); b) enrichment tailings concentration, $x_{ER}$; non-driver fission fraction; c) MOX or NFF core volume fractions, $f_j^f$; d) number of MOX recycles $N_{CYC}$; e) and introduction times and implementation rates of specific fuel cycles, $\tau_j$ and $\lambda_j$. The LMR or FSB options depicted in Figs. 1 are not considered in this study. Results focus primarily on: a) the buildup of plutonium inventories in the five forms listed on Fig. 1 (reactor, REA; LWR-recyclable spent fuel, SF; LWR-unrecyclable spent fuel, SFF; reprocessing, REP; and separated material, SPU); b) costs associated primarily with the fuel cycle in the form of either annual charges, $AC_j$(M$/yr), incremental additions to the cost of electricity, $\Delta$COE(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 integrated accumulation [PRI(ktonne yr), Eq. (8)].

To facilitate comparisons, a base or "point-of-departure" case is defined using a MOX core volume fraction that ultimately reaches $f_{MOX}^f$ = 0.3. After giving key results (*i.e.*, inventory, cost, PRI) for the OT case, similar results for the $f_{MOX}^f$ = 0.3 base case are reported in the following Sec. III.A., which includes an OT-MOX(base-case) comparison. Section III.B. then summarizes results that are pertinent to variations on the MOX and NFF core fractions, with an emphasis given to the former.

All results are based on a single nuclear energy growth scenario described by Eq. (1) and the parameters listed in Table I. All parameters, other than those listed in Table III as subject to parametric variation, are held constant. The nuclear energy growth scenario used in this study largely corresponds to a case that is midway between the low- and medium-variant cases described in a recent IAEA studies.[1,7]

Since the MOX (or EMOX/NFF) core fractions for all scenarios considered are exogenously driven, mismatches between LWR-recyclable plutonium demand and supply in some circumstances can arise. The approach taken in all cases reported herein decreases heretofore growing MOX (or EMOX/NFF) core fractions to bring demand in line with supply; an alternative is to terminated the computation when LWR-recyclable unrealistically goes through zero. Since LMRs and or FSBs are not considered in this study, LWR-unrecyclable plutonium (*e.g.*, having achieved a number of recycles, $N_{CYC}$) simply accumulates.

The neutronics model used to evaluated plutonium inventories in spent fuel arising from the UOX and MOX/EMOX/NFF parts of the core is highly simplified and remains to be calibrated with detailed neutronics and fuel-cycle computations.[8,11] Specifically, net plutonium concentrations in either UOX or MOX/EMOX/NFF parts of the core at end-of-life (EOL) are assumed to equal a constant that is proportionately (linearly) decreased according the uranium content in the respective core sections. The beginning-of-life (BOL) plutonium concentrations in the MOX/EMOX/NFF parts of the core is proportionately and moderately increased as uranium is replaced with zirconium. The EOL concentration of this "driver" plutonium is determined from an exogenous burnup parameter, BU(MWtd/kgHM), which is corrected for: a) density variations incurred during any MOX $\rightarrow$ EMOX $\rightarrow$ NFF transitions (Fig. 3); 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). As will be shown, the degree to which overall plutonium inventories can be reduced (without implementing FSBs) depends on this highly aggregated neutronics parameters, and related variations with core-sector size and composition. Generally, this separation of plutonium into "driver" and "bred-burned" forms is an artifact adopted for the present study and, unfortunately, is not easily computed using conventional neutronic models.

A. Base Case

1. Once-Through LWR Fuel Cycle

The time dependence of plutonium inventories for the OT/LWR case is given in Fig. 6; for this case, $I_{SFF,REP,SPU} = 0$. Also shown on this figure is the time dependence of nuclear capacity, $P_E$, as given by Eq. (1); this demand variant is used for all cases considered in this study. The evolution of spent-fuel age and "creation" distribution for this OT/LWR case, as used in the evaluation of the proliferation risk index [Eq. (9)], is depicted in Fig. 7. Starting with an assumed initial history of spent fuel accumulation, the creation distribution forms a growing continuum as "fresh" (radioactively "hotter", less attractive to a potential proliferater) spent fuel is added to the older inventories. Each vertical line in Fig. 7 represents the start of the respective spent-fuel creation distribution at that time; the average age, $\tau_{SF}$(yr), for this OT/LWR is also shown. Figure 8 gives the time dependence of accumulated uranium usage, $I_U^{MM}$, optimal enrichment tailings composition, $x_{DU}$, and uranium unit cost, $UC_{MM}$, for the Known Resources scenario (KR, Fig. 5) and the OT/LWR case. This unit cost forms one component of the overall fuel-cycle charge, $AC_j$(M\$/yr), which is shown normalized to $P_E$ on Fig 9. Charges related to REP, FP, and SPU are not incurred for the OT/LWR case. These annual charges are then converted through Eqs. (10) and (11) to incremental or total costs of electricity. The time evolution of cost of electricity, COE(mill/kWeh), incremental COE related to the fuel cycle, $\Delta$COE(mill/kWeh), and present value of all fuel cycle charges, $PV_{FC}$(B\$), evaluated over the time of the computation for an cost of money COM = 0.05 1/yr, for the OT/LWR case and uranium resources = KR (Fig. 5), are all shown on Fig. 10. Lastly, Fig. 11 depicts the time evolution of total and component proliferation risk indices, $PRI_j$(ktonne yr), for the OT/LWR case that discounts future risk at a rate r = 0.05 1/yr using the weights listed in Tables I and II.

The results summarized on Figs. 6-11 for the OT/LWR case represent a typical ensemble of inventory, cost, and PRI results for the simplest of cases considered - the evolution of the OT/LWR fuel cycle in a uniform growth/demand scenario. The first series of parametric variations listed in Table III examines for the OT/LWR case a range of uranium resource scenarios (*e.g.*, CR, KR, and TR, as described on Fig. 5). Figure 12 gives the cost impact of this range of uranium resource "realities" on the OT/LWR case. Reflections of these uranium costs on COE and $\Delta$COE (Fig. 10) are given in comparison with the MOX/LWR case in the following section (Fig. 17).

2. Plutonium Recycle Base Case (30% MOX Core Volume Fraction)

Figures 13-18 give for the $f_{MOX}^{f} = 0.3$ MOX/LWR case inventory, spent-fuel age, cost, and PRI impacts similar to those reported in Figs 6-12 for the OT/LWR case. These results pertain to the B-series listed on Table III, with comparison to the previously reported A-series also being given. This $f_{MOX}^{f} = 0.3$ MOX/LWR case is dubbed the "point-of-departure" or base case for this study, with parametric variations away from this base case being reported in the following Sec. III.B.

The time dependence of plutonium inventories for the $f^f_{MOX}$ = 0.3 MOX/LWR base case is given in Fig. 13. For this $N_{CYC}$ = 4 base case, the spent-fuel inventory of LWR-recyclable plutonium, $I_{SF}$, decreases as the inventory of LWR-unrecyclable plutonium, $I_{SFF}$, increases. As will be shown, the $f^f_{MOX}$ = 0.3 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) will push $I_{SF}$ inventories to zero, thereby causing a decrease in $f_j$(j = MOX, EMOX, NFF), as described earlier, to accommodate SF-plutonium supply and demand. Figure 14 gives the evolution of spent-fuel age and creation distribution for the $f^f_{MOX}$ = 0.3 MOX/LWR base case, and also gives a comparison with the OT/LWR case (Fig. 7). 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 by the vertical right segment of a given distribution on Fig. 14). The diminished and diminishing average age of spent fuel for the base case, $\tau_{SF}$(MOX), compared to the OT/LWR case, is also noted. These differences are reflected in the PRI computation, as described in Sec. II.C.

The $P_E$-normalized annual charges for key components of the nuclear fuel cycle for the $f^f_{MOX}$ = 0.3 MOX/LWR base case are illustrated in Fig. 15. A comparison of the total annual charge associated with the fuel cycle for the OT/LWR case (Fig. 9) is also given. The increasing importance of reprocessing cost for the $f^f_{MOX}$ = 0.3 MOX/LWR base case ($AC_{REP}$) is noted, with the reduction in annual charges associated with uranium resource ($AC_{MM}$) eventually causing $AC_{TOT}$(OT/LWR) to increase above $AC_{TOT}$(MOX/LWR) at ~70 years into the computation for this KR uranium resource scenario (Fig. 5). The cost impact of this KR (Known Resource) uranium resource category is shown in comparison with the OT/LWR case depicted on Fig. 16. 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 the 100 \$/kgU base price and the point where enrichment tails, $x_{DU}$, begin to decrease in accordance to Eq. (14) in an effort to minimize overall enrichment charges.

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 comparisons of COE, ΔCOE, and $PV_{FC}$ for these two cases. Figure 17 gives the 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, $PV_{FC}$(B\$), evaluated over the time of the computation for a cost of money COM = 0.05 1/yr, for the $f^f_{MOX}$ = 0.3 MOX/LWR case and the three categories of uranium resources (CR, KR, TR, Fig. 5). All resource cases show an initial increase in COE or ΔCOE for the MOX/LWR case above that of the OT/LWR case. Depending on the uranium resource scenario and the associated uranuim unit-cost scaling, 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 heavily 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” (Fig. 17).

Lastly, Fig. 18 gives the time evolution of total and component proliferation risk indices, $PRI_j$(ktonne yr), for the $f^f_{MOX}$ = 0.3 MOX/LWR case that discounts risk at a rate r = 0.05 1/yr using the weights listed in Tables I and II. A comparison of the total PRI for the OT/LWR case reported on Fig. 11, as well as for a MOX/EMOX/NFF scenario reported in Sec. III.B.4, is given. As for the OT/LWR case (Fig. 11), plutonium in SF (recyclable to LWRs) presents the greater PRI for the weights used in Table I and II. 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. Parametric Variations Around Base Case

While not complete, the impacts of parametric variations away from the $f^f_{MOX}$ = 0.3 MOX/LWR base case are examined in this section. These impacts are displayed largely 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 pulls back on the programmed increase in the relevant core fraction, $f_j$(j = MOX, EMOX, NFF), in order to force an equilibrium between SF-plutonium supply and demand. These triggerings are reflected in subsequent inventory and cost trajectories. The following subsections examine the impacts of four important scenario attributes: a) the driver fuel fission fraction, $f_{DF}$ = 1 – $f_{Pu}$; b) the number of MOX recycles, $N_{CYC}$, beyond which on average the discharged MOX is declared inefficient for use in a thermal-spectrum reactor; c) the asymptotic MOX core volume fraction, $f^f_{MOX}$ (= 0.3 for the base case); and d) a transition to NFF operation.

### 1. Driver-Fuel Fission Fraction

As discussed at the beginning of this section, the plutonium balances are base on a highly simplified neutronics model that specifies the EOL concentrations of plutonium bred into either the UOX or MOX/EMOX/NFF regions, as well as the fraction of all energy (fissions) generated in 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. As is indicated in Table I, the driver-fuel fission fraction for all computations is fixed at $f_{DF}$ = 0.6; 40% of the energy released and included in the burnup parameter, BU, is assumed to occur in fissile material not original loaded into the fuel assembly. The sensitivity of the accumulated plutonium inventories to the values assumed for $f_{Pu}$ is shown in Fig. 19 for the $N_{CYC}$ = 4, $f^f_{MOX}$ = 0.3 MOX/LWR base case for BU = 40 MWtd/kgHM. 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. 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. 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. Figure 20 shows the impact of reducing $N_{CYC}$ on SF, SFF, and total plutonium inventories, in comparison to the base case. As expected, lowering 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 $I_{SF}$ does not go negative. As is indicated on Fig. 20, the total plutonium inventory is only moderately impacted 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 overridden to maintain a balance between supply and demand. This behavior is shown on Fig. 21, which gives a range of $f_{MOX}$ trajectories as $f^f_{MOX}$ is varied. The impact on the average age of spent fuel in this system is depicted on Fig. 22. Lastly, Figure 23 gives the time dependence of key plutonium inventories for the range of $f^f_{MOX}$ values examined. The OT/MOX case is designated by $f^f_{MOX}$ = 0.0. Otherwise, all values are as described in Table I for the $f^f_{MOX}$ = 0.3 MOX/LWR base case ($f_{Pu}$ = 0.4, $N_{CYC}$ = 4, *etc*.).

4. Transitions to Non-Fertile Fuels

The UOX → MOX → EMOX → NFF scenario depicted in Fig. 3 is examined in terms of the three top-level assessment criteria adopted for this study: plutonium inventories; costs; and proliferation-risk indices. As described in Sec. II.A., the removal of uranium from MOX and replacement by zirconium will both 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. 24, which compares the plutonium inventory transients for the OT/LWR (Sec. III.A.1.), MOX/LWR (base case, Sec. IIIA.2.), and the UOX → MOX → EMOX → NFF scenario (Fig. 3). The comparable comparison of costs given on Fig. 25 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 scenarios tracks the resource-driven higher COEs that plague OT/LWRs in the out years. On a present-value basis, which, as noted above, 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 latter 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 MOX/LWR base case.

Lastly, the impacts on the total PRI of the the main scenarios considered in this study are shown on Fig. 26. Relative to the OT/LWR scenario (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.

## IV. SUMMARY AND CONCLUSION

A simplified and highly aggregated global model has been used to evaluate interactions and trade offs between: a) plutonium inventories in five forms [*e.g.*, reactor(REA), LWR-usable spent fuel(SF), LWR-unusable spent fuel (SFF), reprocessing (REP), and separated (SPU)]; b) fuel cycle and total energy costs; and b) a crude, inventory-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 phenomena rather than to present firm conclusion and recommendations. The sensitivity of key metrics for assumed neutronics performance suggests a stronger coupling with basic core neutronics computations is needed in future studies. Also, improved PRI metrics[18] that better assess risk and consequence is needed. Key interim findings from this systems study are:

- The impact on cost of uranium resource depletion for the once-through LWR scenario will be felt for the Known Resources (KR) scenario (Fig. 5B) within ~50 years for the median growth scenario used throughout this investigation (~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 (Fig. 12).

- A comparison of the total annual charges associated with the fuel cycle for the OT/LWR and MOX/LWR cases illustrates the increasing importance of reprocessing cost for this 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 (Fig. 5).

- 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 $\gtrsim$ 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 (COM = 5%/yr) 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 heavily 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 (Fig. 11), plutonium in the SF inventories (recyclable to LWRs) presents the greater PRI for the 30% MOX/LWR and for the weights used. 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.

- 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) will push $I_{SF}$ inventories to zero, thereby causing a decrease in $f_j$(j = MOX, EMOX, NFF), as described earlier, to accommodate SF-plutonium supply and demand; this condition and the resulting material-conserving feedback impacts all subsequent results (*e.g.*, $f^f_{MOX}$, $N_{CYC}$, compositional and/or neutronics parameter variations).

- 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 $I_{SF}$ does not go negative; the total plutonium inventory, however, is only moderately impacted for $N_{CYC} \geq 2$.

- The removal of uranium from MOX and replacement by zirconium will both increase 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 $\rightarrow$ MOX $\rightarrow$ EMOX $\rightarrow$ NFF scenario initially tracks the MOX/LWR (higher COEs than the OT/LWRs), but at later times this scenarios tracks the resource-driven higher COEs that plague OT/LWRs in the out years. On a present value basis, the UOX $\rightarrow$ MOX $\rightarrow$ EMOX $\rightarrow$ NFF scenario largely follows that of the MOX/LWR base case. The latter 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 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 30% MOX/LWR base case.

NOMENCLATURE

| | |
|---|---|
| $A_j$(kg/kole) | atomic weight of $j^{th}$ species |
| $AC_j$(M$/yr) | annual charge associated with $j^{th}$ component of fuel cycle |
| ATW | accelerator transmutation of waste |
| a | fitting parameter, $P_E(\infty)/P_E(0)$ |
| $a_{ij}$ | relative importance in Saaty's pairwise matrix, $w_i/w_j$ |
| B | plutonium “burner” (FSB) |
| BOL | beginning of life |
| BR | breeding ratio (LMR) |
| BU(MWtd/kgHM) | burnup parameter |
| CAP | capital charges |
| COE(mill/kWeh) | cost of electricity |
| COM(1/yr) | cost of money, discount rate |
| CR | conversion ration (LMR), conventional (uranium) resource category[22] |
| CV | conversion ($U_3O_8 \rightarrow UF_6$) |
| DB,DP | “burner”, “producer” plutonium demand |
| DU | depleted uranium |
| DPY | days per year, 365 |
| $dI_{SF}$(kgPu) | spent-fuel creation distribution |
| $E_f$(Mev/fission) | energy released per fission, 200 |
| EOL | end of life |
| EMOX | evolutionary MOX (MOX + NFF) |
| ER | uranium isotope enrichment |
| EU | enriched uranium |
| $EXP_j$(ktonne yr) | exposure (to risk) of plutonium in form j (REA, SF, REP, SPU) |
| e(eV/J, coulomb) | electronic charge, $1.6021\times10^{-19}$ |
| FC | fuel cycle |
| FCR(1/yr) | fixed charge rate |
| FF | fuel fabrication |
| FP | fission product |
| FPD(d) | full-power day |
| FSB | fast spectrum burner (LMR/IFR, ATW) |
| $f_B^{Pu}$ | burnup fraction of driver (original) plutonium loading |
| $f_{COOL}$ | coolant volume fraction |
| $f_{DF}$ | driver fuel fission fraction, $1 - f_{Pu}$ |
| $f_i$ | core (volume) fraction of $i^{th}$ fuel form (i= UOX, MOX, EMOX, NFF) |
| $f_{LWR}$ | fraction of $P_E$ delivered by LWRs, $\rho/(1 + \rho)$ |
| $f_{MOX}^f$ | final or asymptotic MOX (or NFF) core volume fraction |
| $f_{OM,OP}$(1/yr) | O&M or operations charge rate as a fraction of total capital cost |
| $f_{Pu}$ | fraction of fissions occurring in material other than driver fuel |
| g | logit function describing growth of nuclear energy |
| HM | heavy metal (Pu, U, also NF material) |
| HPY | hours per year, 8760 |
| $I_j$(kg) | plutonium inventory in $i^{th}$ form (j = REA, SF, SFF, SPU, REP) |
| $I_U^{MM}$(Mtonne) | cumulative (worldwide) uranium ore mined |

| | |
|---|---|
| IFR | integral fast reactor |
| KR | known (uranium) resource category[22] |
| LMR | liquid metal (fast) reactor |
| LWR | light water reactor |
| $M_U$(Mtonne) | cumulative (worldwide) uranium ore mined |
| MM | mining and milling |
| MOX | mixed (Pu,U) oxide fuel |
| $N_A$(entities/mole) | Avagadro's number, $6.0249\times10^{23}$ |
| $N_{CYC}$ | number of LWR recycles before plutonium is declared unusable by LWR |
| NF | nonfertile material (Zr) |
| NFF | nonfertile fuel |
| NU | natural uranium |
| OECD | Organization Economic Cooperation and Development |
| O&M,OM | operations and maintenance |
| OP | operations |
| OT | once-through LWR fuel cycle ( $f^f_{MOX} = 0.0$) |
| P | plutonium “producer” (LWR), or plutonium production |
| $P_E$(MWe) | net-electric capacity, $P_B + P_P$ |
| $P_B$(MWe) | net-electric capacity associated with burner (FSB) |
| $P_P$(MWe) | net-electric capacity associated with producer (LWR) |
| PD(MWt/m$^3$) | average core power density |
| PRI(ktonne yr) | total weighted proliferation risk index |
| $PRI_j$(ktonne yr) | proliferation risk index of plutonium in form j (REA, SF, REP, SPU) |
| $PV_{FC}$(B$) | present value of total fuel-cycle charges |
| $p_f$ | plant availability |
| $R_i$(kgPu/yr) | mass flow rates (i = P, SF, SFF, REP, DP, DB) |
| REA | reactor plutonium inventory |
| REP,RP | plutonium in reprocessing |
| RU | recycled uranium |
| r(1/r) | discount rate use to reduce the importance of future risks |
| $r_B$(kgPu/yr/MWe) | normalized burnup rate |
| $r_P$(kgPu/yr/MWe) | normalized production rate |
| SF | LWR-recyclable plutonium in spent fuel, or spent fuel in general |
| SFF | LWR-unrecyclable plutonium in spent fuel |
| SI(kgHM/MWt) | specific inventory |
| SP(MWt/kgHM) | specific power |
| SPU | separated plutonium (FF plus ready inventories) |
| SPY | seconds per year, $3.15\times10^7$ |
| SWU | separative work unit |
| TR | total (uranium) resource category[22] |
| TOT | total (plutonium) |
| t(yr) | time |
| $U_1$ | uranium cost parameter |
| $UC_j$($/unit) | unit cost associated with $j^{th}$ operation or system |
| UOX | uranium oxide fuel |
| UTC($/We) | unit total (capital) cost |
| $w_i$ | weights used in Saaty's pairwise matrix to determine $PRI_j$ |
| $x_j$ | concentration |

| | |
|---|---|
| $x^{i}_{Pu}$ | plutonium driver-fuel weight fraction in $i^{th}$ core region |
| $x_{Zr,U}$ | NF and (depleted, natural) uranium atom fractions in EMOX |
| $y^{i}_{Pu}$ | plutonium bred-fuel weight fraction in $i^{th}$ core region |
| | |
| $\alpha$(kgPu/MWt/yr) | fission release, SPY($A_{49}$/1000)/(e $N_A$ $E_F$), 0.3901 |
| $\Delta$COE(mill/kWeh) | incremental COE associated with fuel cycle |
| $\Delta x_{Pu}$ | plutonium burnup fraction, $x^{BOL}_{Pu} - x^{EOL}_{Pu}$ |
| $\eta_{TH}$ | thermal conversion efficiency |
| $\phi(x)$ | uranium enrichment potential, $(2x-1)\ln[x/(1-x)]$ |
| $\lambda_P$(1/yr) | nuclear energy growth rate |
| $\lambda_{AGE}$(1/yr) | decay rate of radiation proliferation shield protecting SF plutonium |
| $\nu$ | uranium cost parameter |
| $\rho$ | ratio of burner-to-producer electrical powers, $P_P$(LWR)/$P_B$(FSB) |
| $\rho_j$(kg/m$^3$) | density of $j^{th}$ material/region, includes coolant voids ($f_{COOL}$) |
| $\tau_j$(yr) | time constant or holdup time for $j^{th}$ process (j = REP,SPU,REA); or time when specific core transitions commences (j = MOX,EMOX,NFF) |
| $\tau_{SF}$(yr) | average age of spent fuel |
| $\zeta$ | atom ratio of NF material (natural, depleted) uranium |

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Table I. Typical Input Parameters

| | |
|---|---|
| SYSTEM PARAMETERS | |
| Initial power, $P_{Eo}$(MWe) | 340,000. |
| Final power, $P_{Ef}$(MWe) | 1,000,000. |
| Asymptotic power, $P_{E\infty}$(MWe) | 1,436,427. |
| Power ratio, $P_{E\infty}/P_{Eo}$ | 4.23 |
| Normalized power growth rate, $\lambda_P$(1/yr) | 0.0200 |
| Thermal efficiency for producer (LWR), $\eta_{TH}^{P}$ | 0.3250 |
| Thermal efficiency for burner(LMR), $\eta_{TH}^{B}$ | 0.4000 |
| Engineering gain for producer (LWR), $Q_E^P$ | 25.0 |
| Engineering gain for burner (LMR), $Q_E^B$ | 25.0 |
| Plant capacity factor for producer (LWR), $p_{fP}$ | 0.75 |
| Plant capacity factor for burner (LMR), $p_{fB}$ | 0.75 |
| Producer normalized Pu consumption rate, $r_b$(kg/MWe/yr) | 1.2010 |
| Producer normalized Pu production rate, $r_p$(kg/MWe/yr) | 0.2808 |
| Burner normalized Pu consumption rate, $r_b'$ (kg/MWe/yr) | 0.9758 |
| Burner normalized Pu production rate, $r_p'$ (kg/MWe/yr) | 1.1406 |
| Intial support ratio, $\rho_o = (P_E^P / P_E^B)_o$ | 1000.[(a)] |
| Final support ratio, $\rho_f = (P_E^P / P_E^B)_f$ | 1000.[(a)] |
| Normalized support ratio rate, $\lambda_\rho$(1/yr) | 0.0[(a)] |
| Initial burner breeding ratio, $BR_o$ | 0.90 |
| Final burner breeding ratio, $BR_f$ | 1.00 |
| Burner breeding ratio rate, $\lambda_{BR}$(1/yr) | 0.0 |
| INITIAL CONDITIONS | |
| Intial total power, $P_{Eo}$(MWe) | 340,000. |
| Initial separated plutonium inventory, $I_{SPUo}$(kg) | 0.0 |
| Initial spent-fuel plutonium inventory, $I_{SFo}$(kg)/$10^7$ | 7.0 |
| Average age of initial spent-fuel inventory, $\tau_{SF}$(yr) | 30.0 |

Table I. Typical Input Parameters (Cont-1)

| | |
|---|---|
| SCENARIO PARAMETERS | |
| Initial MOX/EMOX/NFF core fraction, $f_{TOTo}$ | 0.0 |
| Final MOX/EMOX/NFF core fraction, $f_{TOTf}$ | 0.30 |
| UOX $\rightarrow$ MOX transition time, $\tau_{MOX}$(yr) | 5.0 |
| MOX $\rightarrow$ EMOX transition time, $\tau_{EMOX}$(yr) | 25.0 |
| Normalized MOX buildup rate, $\lambda_{MOX}$(1/yr) | 0.10 |
| Initial NFF core fraction, $f_{NFFo}$ | 0.0 |
| EMOX $\rightarrow$ NFF incremental core fraction, $\Delta f_{NFFf}$ | 0.0 |
| Final NFF core fraction, $f_{NFFf} = f_{MOX} = \Delta f_{NFF}$ | 0.30 |
| Normalized NFF buildup rate, $\lambda_{NFF}$(1/yr) | 0.03 |
| Initial EMOX $Zr0_2/(UO_2 + ZrO_2)$ ratio, $\zeta_o$ | 0.00 |
| Final EMOX $Zr0_2/(UO_2 + ZrO_2)$ ratio, $\zeta_f$ | 1.00 |
| EMOX $\rightarrow$ NFF transition, $\zeta_{CRT} = [Zr0_2/(UO_2 + ZrO_2)]_{CRT}$ | 0.80 |
| EMOX $Zr0_2/(UO_2 + ZrO_2)$ time constant, $\lambda_\zeta$(1/yr) | 0.10 |
| URANIUM PARAMETERS | |
| Uranium ore grade (weight fraction), $x_{ORE}/10^6$ | 5.00 |
| $^{235}U$ concentration in enriched uranium, $x_{EU}$ | 0.0400 |
| Optimized $^{235}U$ concentration in depleted uranium, $x_{DU}$ | 0.00438 |
| $^{235}U$ concentration in recycled uranium, $x_{RU}$ | 0.01476 |
| $^{235}U$ concentration in natural uranium, $x_{NU}$ | 0.00717 |
| Accumulated uranium usage (1995), $I_{MMo}$(kg)$/10^8$ | 2.00 |
| Initial depleted uranium (1995), $I_{DUo}$(kg)$/10^8$ | 1.84 |
| Initial recycled uranium (1995), $I_{RUo}$(kg)$/10^7$ | 1.57 |

Table I. Typical Input Parameters (Cont-2)

| | |
|---|---|
| FUEL/CORE PARAMETERS | |
| Fuel burnup for producer (LWR), $BU_p$(MWtd/kgHM) | 40. |
| Fuel burnup for burner (LMR), $BU_b$(MWtd/kgHM) | 80. |
| Fraction UOX fissions not in $^{235}U$, $f_{Puo}$ | 0.40 |
| Producer spent-fuel Pu fraction in UOX, $x_{Pu}^{UOX}$ | 0.0100 |
| Producer MOX plutonium fraction, $x_{Pu}^{MOX}$ | 0.0500 |
| NFF plutonium fraction, $x_{Pu}^{NFF}$ | 0.0812 |
| Burner plutonium fraction, $x_{Pub}$ | 0.1000 |
| Producer specific inventory, $SI_P$(kg/MWe) | 82.2 |
| Burner (LMR) specific inventory, $SI_B$(kg/MWe) | 169.0 |
| Nominal producer (LWR) core power density, PD(MWt/$m^3$) | 85.0 |
| Nominal material densities, $\rho_{jo}$(kg/$m^3$): | |
| • $UO_2$ | 10,000. |
| • $ZrO_2$ | 5,600. |
| • $PuO_2$ | 10,000. |
| • $H_2O$ | 650. |
| • $(U,Pu)O_2$ | 10,000. |
| • $(Zr,Pu)O_2$ | 5,993. |
| Coolant volume fraction, $f_{COOL}$ | 0.40 |
| Core averaged densities, $\rho_j$(kg/$m^3$): | |
| • UOX region | 6,260. |
| • MOX region | 6,260. |
| • NFF region | 3,856. |
| Specific powers, $SP_j$(MWt/kg): | |
| • UOX region | 0.0136 |
| • MOX region | 0.0136 |
| • NFF region | 0.0220 |
| Power densities, $PD_j$((MWt/$m^3$): | |
| • UOX region | 85.0 |
| • MOX region | 85.0 |
| • NFF region | 85.0 |
| PROCESS PARAMETERS | |
| Inventory time for natural uranium, $\tau_{NU}$(yr) | 10.0 |
| Inventory time for enriched uranium, $\tau_{EU}$(yr) | 10.0 |
| Separated plutonium residence time, $\tau_{SPU}$(yr) | 0.10 |
| Reprocessing residence time, $\tau_{RP}$(yr) | 0.50 |

Table I. Typical Input Parameters (Cont-3)

| | |
|---|---|
| PROLIFERATION-RISK PARAMETERS | |
| Risk discount rate, r(1/yr) | 0.05 |
| Initial PRI stream weights | |
| • active reactor inventory, $w_{REA}$ | 0.05 |
| • spent fuel, $w_{SF}$ | 0.10 |
| • reprocessing/fuel fabrication, $w_{RP}$ | 0.30 |
| • stored separated, $w_{SPU}$ | 0.55 |
| COSTING/ECONOMICS PARAMETERS | |
| Fitting constant for uranium ore cost (KR case)(b) | |
| • pre-exponential factor, $U_1/10^{11}$ | 6.84 |
| • exponential factor, ν | 1.26 |
| Unit costs: | |
| • uranium ore (1990), $UC_{MMo}$($/kgU) | 100.0 |
| • uranium conversion, $UC_{CV}$($/kgU) | 5.0 |
| • uranium separative work, $UC_{SW}$($/kg SW) | 100.0 |
| • uranium fuel fabrication, $UC_{FF}^{UOX}$ ($/kgHM) | 200.0 |
| • MOX fuel fabrication, $UC_{FF}^{MOX}$ ($/kgHM) | 400.0 |
| • spent-fuel storage, $UC_{SF}$($/kg/yr) | 10.0 |
| • fission product storage, $UC_{FP}$($/kg/yr) | 10.0 |
| • spent-fuel/fission-product transport, $UC_{TR}$($/kg)0.0 | |
| • reprocessing producer (LWR) fuel, $UC_{RP}^{P}$ ($/kgHM) | 1,000.0 |
| • reprocessing burner (LMR), $UC_{RP}^{B}$ ($/kgHM) | 1,500.0 |
| • unit total cost for producer (LWR), $UTC_P$($/We) | 2.50 |
| • unit total cost for burner (LMR), $UTC_B$($/We) | 3.75 |
| Cost of money, COM(1/yr) | 0.050 |
| Fixed charge rate for producer (LWR), $FCR_P$(1/yr) | 0.090 |
| Fixed charge rate for burner(LMR), $FCR_B$(1/yr) | 0.090 |
| O&M charge rate for producer (LWR), $f_{OM}^{P}$(1/yr) | 0.020 |
| O&M charge rate for burner(LMR), $f_{OM}^{B}$(1/yr) | 0.020 |

(a) LMR burner not introduced in this study.

(b) Refer to Fig. 5B.

Table II. Pairwise Relative Weights Used to Evaluate Stream/Inventory Proliferation Risk Indices[a]

| i/j | REA | SF | SPU | RP |
|---|---|---|---|---|
| REA | 1/1 | 1/4[b] | 1/8 | 1/6 |
| SF | | 1/1 | 4/8[b] | 4/6[b] |
| SPU | | | 1/1 | 8/6 |
| RP | | | | 1/1 |

[a] Each element of the pairwise comparison matrix is the relative weights, $a_{ij} = w_i/w_j$, and is measured on an importance scale of $w_i = 1$ (least important) to $w_i = 9$ (most important).

[b] The importance or weighting of spent fuel is expected to vary with the age of the spent fuel and is varied accordingly; the values given here for these matrix element are considered representative and are consistent with the other elements. Referring to Eq. (9), $a^{o}_{REA,SF}$ (low $\tau_{SF}$) = 1/2 and $a^{f}_{REA,SF}$(high $\tau_{SF}$) = 1/7.

TABLE III. Summary of Cases Examined

| Case | Description | World | Uranium | MOX[c] | | | EMOX[c] | | | NFF[c] | | | Uranium | Number | Fraction |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Nuclear Growth (%/a)[a] | Resource category[b] | Intro. $\tau_{MOX}$ (yr) | Growth $\lambda_{MOX}$ (1/yr) | Final Fraction $f_{MOX}$[e] | Intro. $\tau_{MOX}$ (yr) | Growth $\lambda_{MOX}$ (1/yr) | Final Fract. $f_{MOX}$[e] | Intro. $\tau_{MOX}$ (yr) | Growth $\lambda_{MOX}$ (1/yr) | Final Fraction $f_{MOX}$[e] | Tailing Option[d] | Recycles $N_{CYC}$[g] | non-driver fissions $f_{Pu}$ |
| A1 | OT/LWR | 1.5→0.6 | CR | (f) | | | | | | | | | opt | | 0.4 |
| A2 | OT/LWR | 1.5→0.6 | KR | | | | | | | | | | opt | | 0.4 |
| TR | OT/LWR | 1.5→0.6 | TR | | | | | | | | | | opt | | 0.4 |
| B1 | MOX/LWR | 1.5→0.6 | CR | 5 | 0.1 | 0.3 | | | | | | | opt | 4 | 0.4 |
| B2 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.3 | | | | | | | opt | 4 | 0.4 |
| B3 | MOX/LWR | 1.5→0.6 | TR | 5 | 0.1 | 0.3 | | | | | | | opt | 4 | 0.4 |
| C1 | OT/LWR | 1.5→0.6 | KR | | | | | | | | | | fix | 4 | 0.4 |
| C2 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.3 | | | | | | | fix | 4 | 0.4 |
| D1 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.3 | | | | | | | opt | 4 | 0.5 |
| D2 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.3 | | | | | | | opt | 4 | 0.3 |
| E1 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.2 | | | | | | | opt | 4 | 0.4 |
| E2 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.25 | | | | | | | opt | 4 | 0.4 |
| E4 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.35 | | | | | | | opt | 4 | 0.4 |
| E5 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.4 | | | | | | | opt | 4 | 0.4 |
| F1 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.3 | | | | | | | opt | 3 | 0.4 |
| F2 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.3 | | | | | | | opt | 2 | 0.4 |
| F3 | MOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.3 | | | | | | | opt | 1 | 0.4 |
| G1 | EMOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.3 | 25 | 0.0 | 0.3 | 0.8 | 0.03 | 0.3 | opt | 4 | 0.4 |
| G2 | EMOX/LWR | 1.5→0.6 | KR | 5 | 0.1 | 0.2 | 25 | 0.0 | 0.2 | 0.8 | 0.03 | 0.2 | opt | 4 | 0.4 |
| G3 | EMOX/LWR | 1.5→0.6 | KR | 5 | 0.2 | 0.2 | 25 | 0.0 | 0.2 | 0.8 | 0.03 | 0.3 | opt | 4 | 0.4 |

(a) initial $\rightarrow$ final(100 yr) growth rates base on a logit function [Eq. (1)], with an average growth rate of 1.0%/a, which over a 100-year interval increases world nuclear power from 340 Gwe to 1,000 Gwe.

(b) CR = Conventional Resources; KR = Known Resources; and TR = Total Resources.

(c) $\tau_j$ is the time of introduction, $\lambda_j$ is the exponentiation time to a final core volume fraction $f_j^f$, where j = MOX, EMOX, NFF; the EMOX $\rightarrow$ NFF transition is assumed to occur at a critical value of the ratio $\zeta$= Zr/(Zr + U).

(d) opt = optimized based on fixed cost of enrichment (100 $/SWU) and the evolving price or uranium ore for a given uranium resource class[(b)]; fix = uranium tailings fraction fixed at the weight fraction $x_t$ = 0.035.

(e) operational goals that are superceded by reductions related to constraints on recyclable spent-fuel poutonium inventories

(f) blanks indicate nonapplicability for the case described.

(g) the parmeter $N_{CYC}$ gives the probability $1/N_{CYC}$ that the MOX fuel discharged from a large ensemble of LWRs will have a total (multiple) exposure that renders the plutonium contained therein inefficient or use in a thermal spectrum reactor.

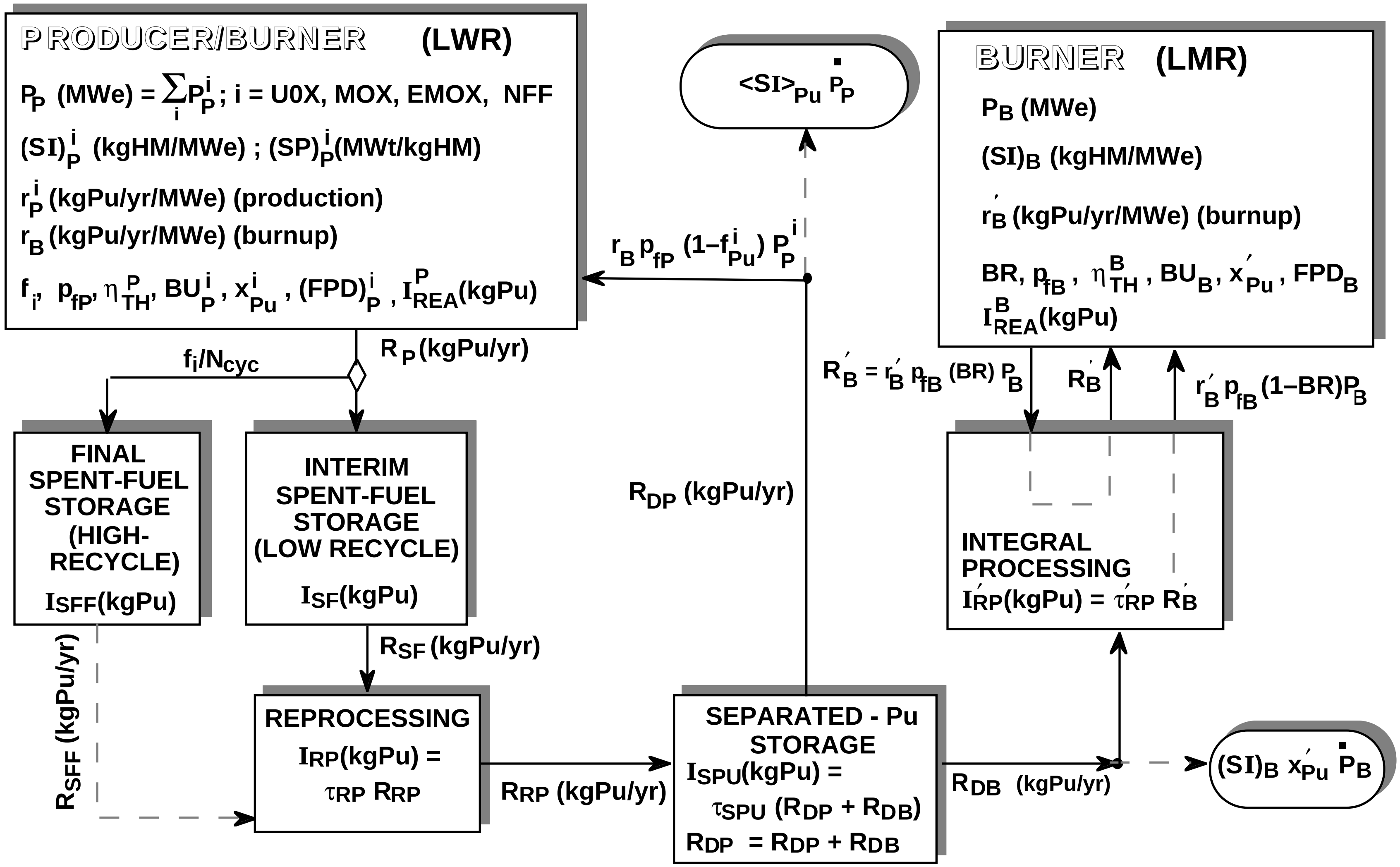


Figure 1. Global plutonium flow model in a systems comprising plutonium producers (LWRs) and plutonium burners (LMRs); the producer can also burn plutonium, and as such is termed a producer/burner.

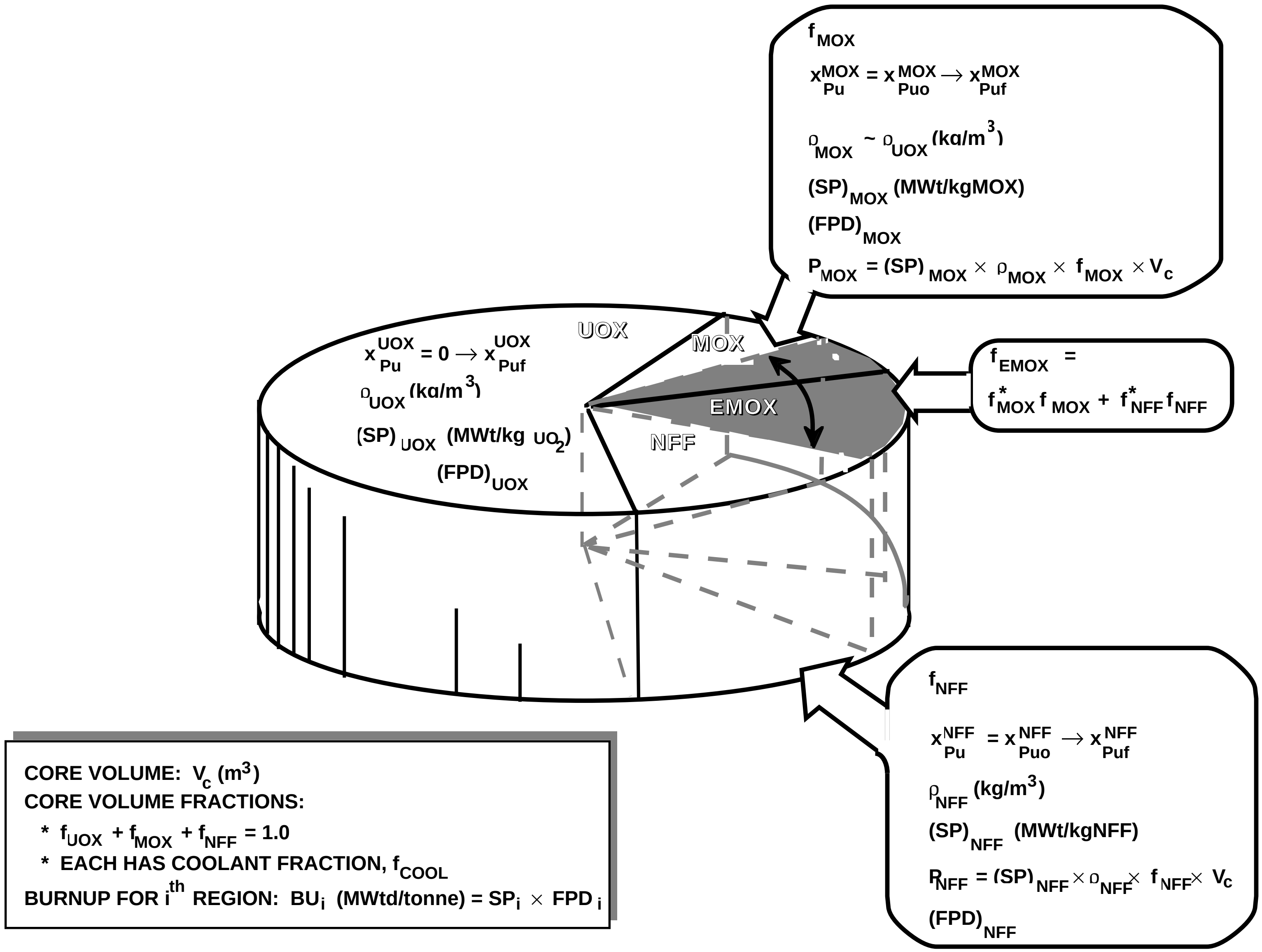


Figure 2. LWR plutonium producer/burner core-segmentation/composition model.

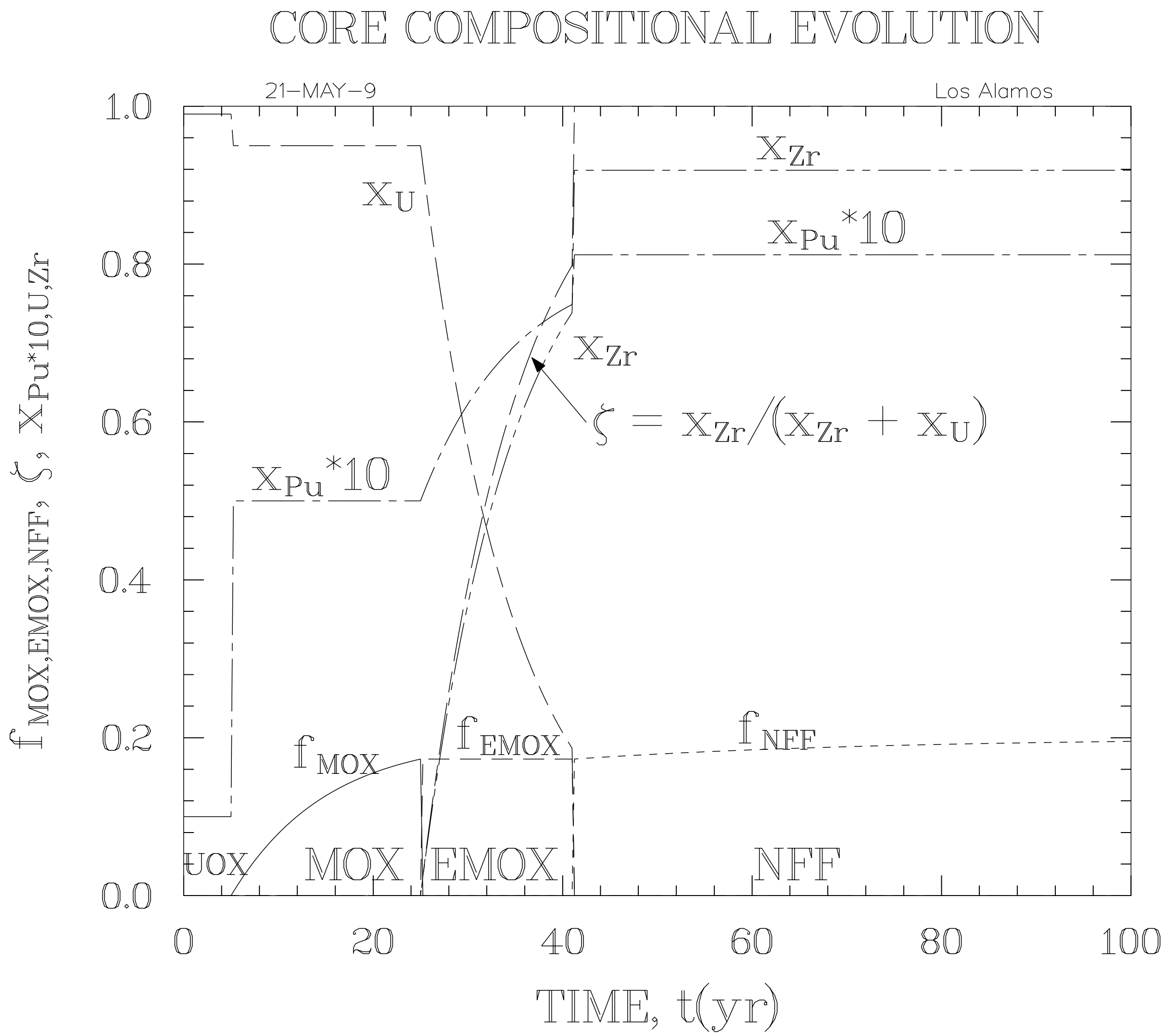


Figure 3. LWR plutonium producer/burner core segmentation/composition evolution model.

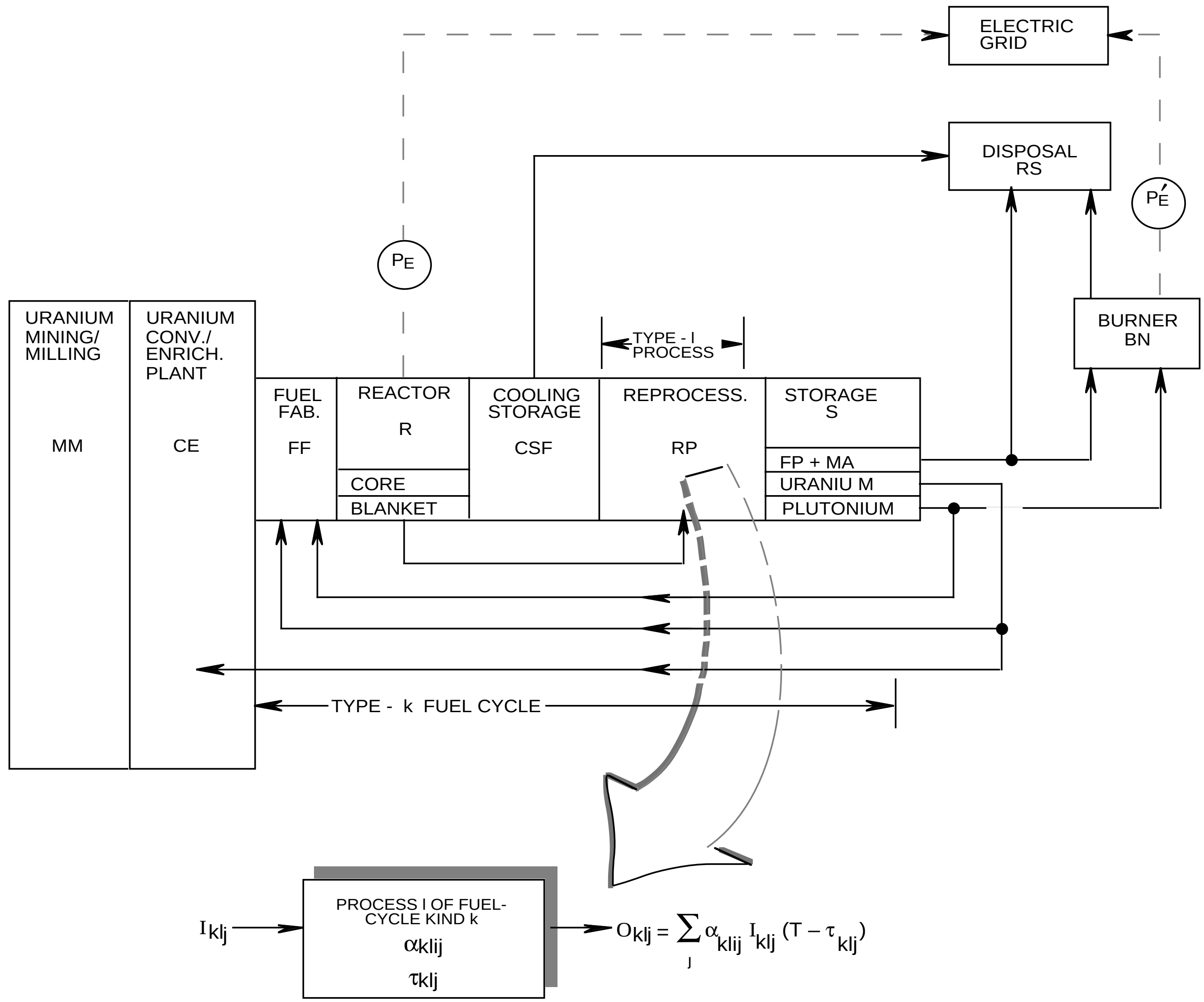


Figure 4. Diagram showing generic fuel-cycle "building blocks" for use in projecting resource-constrained, multi-variable optimization[25] of nuclear energy mixes and material flows.

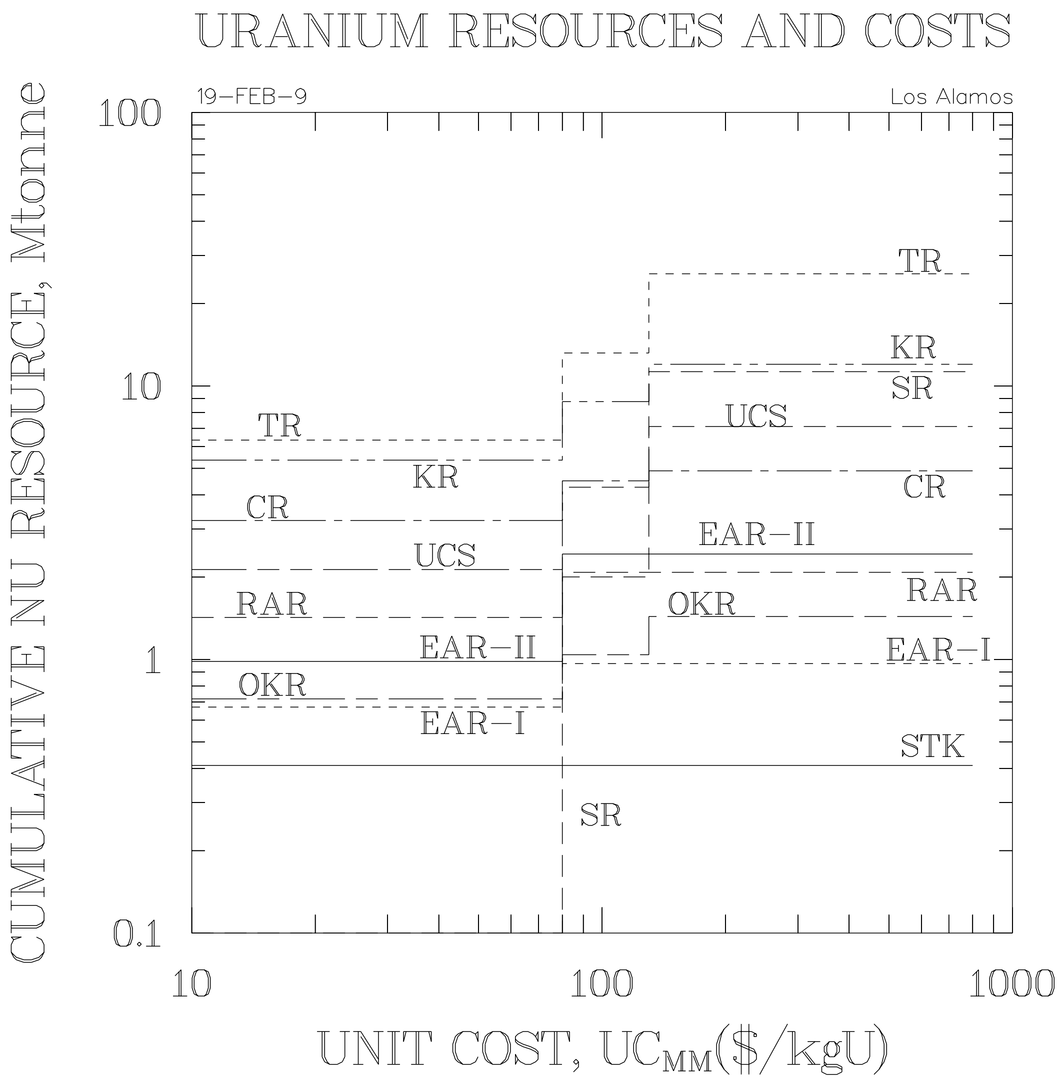


Figure 5A. Uranium resources versus cost in various categories from Ref. 22, as interpreted in Ref. 23; definitions:
STK: Stocks plus Arms Reduction Releases;
RAR: Reasonably Assured Resources;
EAR-I: Estimated Additional Reserves, Category I;
OKR: Other Known Resources;
CR: Conventional Resources;
STK + RAR + EAR-I + OKR UCS: Unconventional and Byproduct Sources;
KR: Known Resources, CR + UCS;
EAR-II: Estimated Additional Reserves, Category II;
SR: Speculative Resources;
TR: Total Resources, KR + EAR-II + SR.

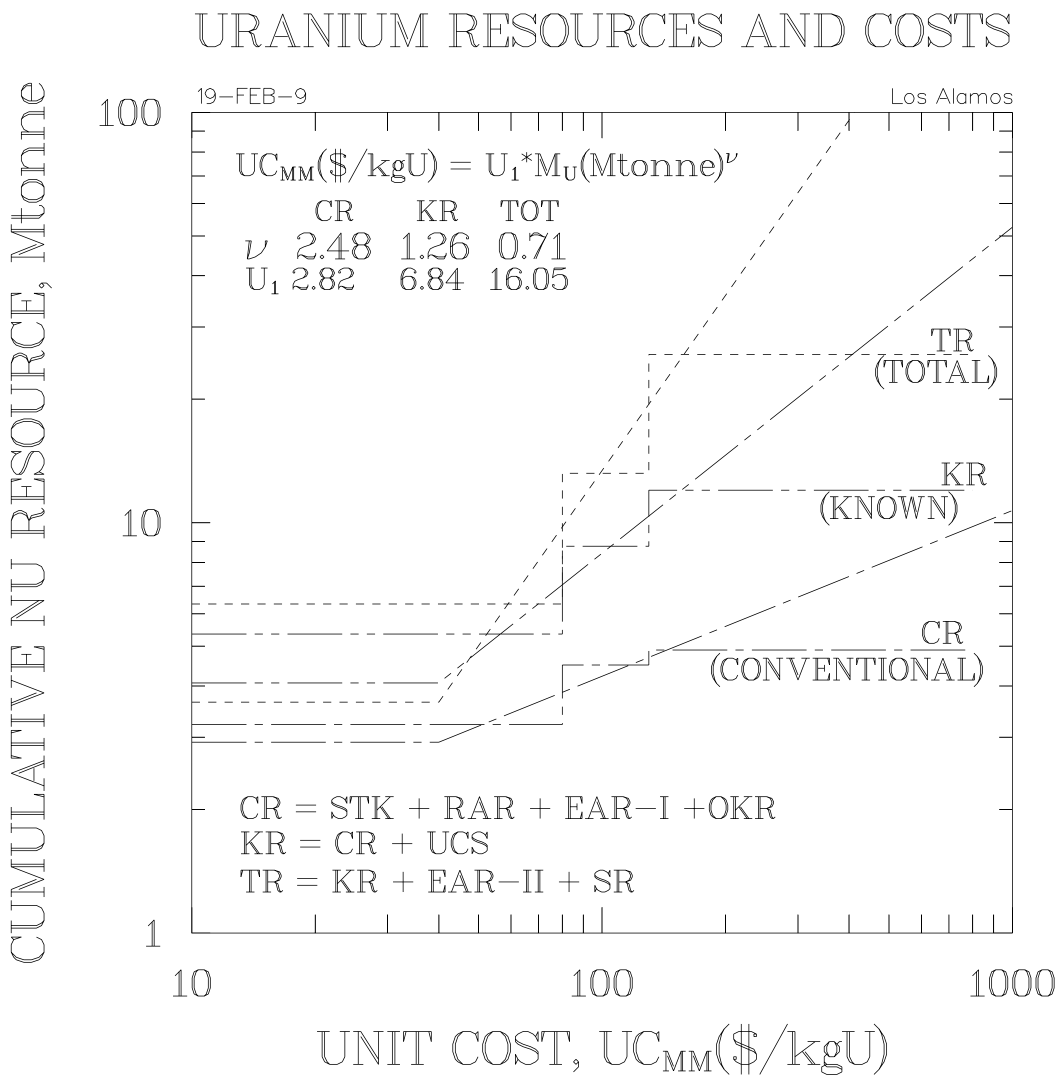


Figure 5B. Uranium resources versus cost for Conventional Reserves (CR), Known Reserves (KR), and Total Reserves (TR), along with parameter fits used in this study.

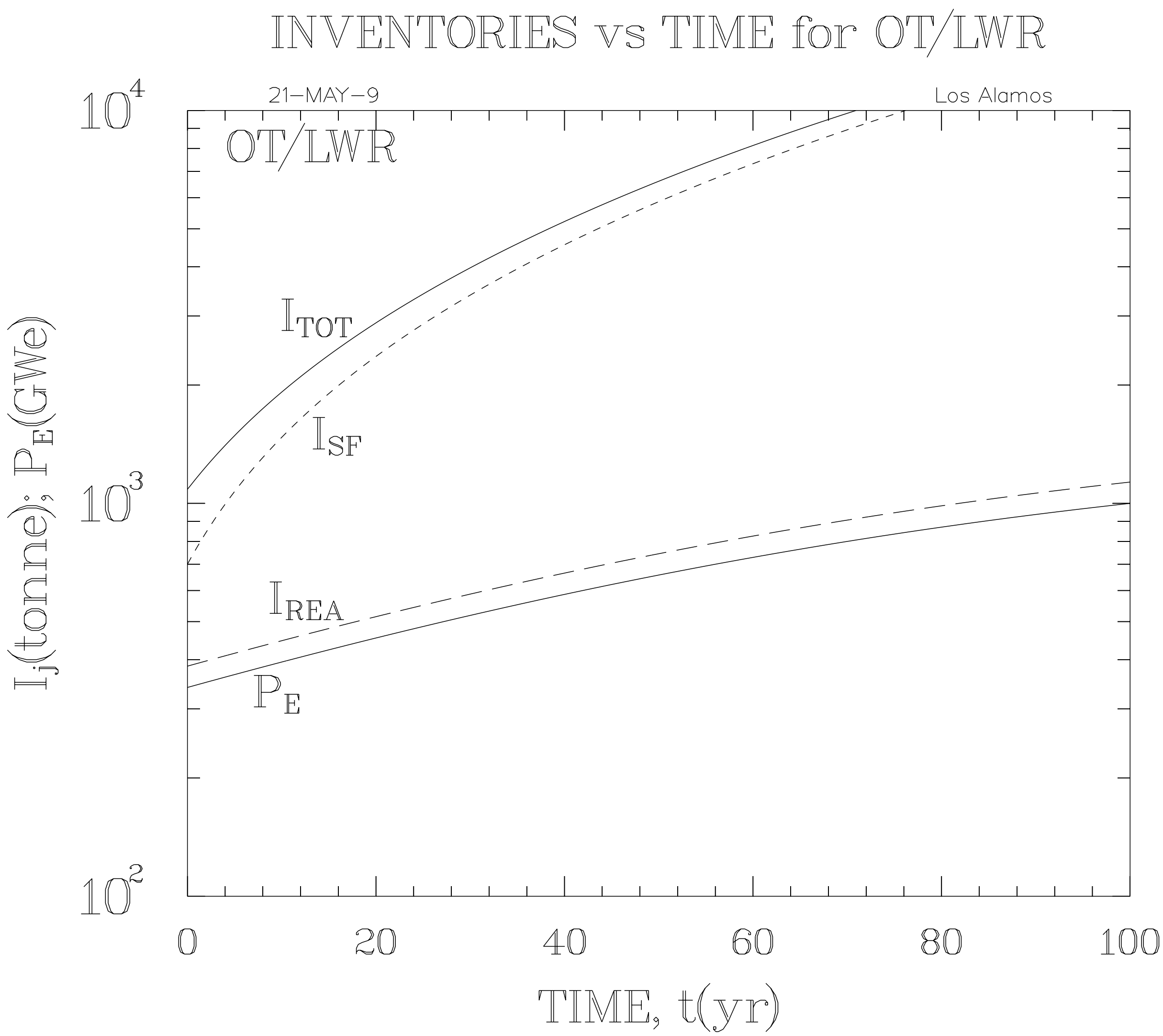


Figure 6. Time dependence of plutonium inventories for the OT/LWR case; for this case, $I_{SFF,REP,SPU} = 0$. Also shown is the time dependence of nuclear capacity, $P_E$, as given by Eq. (1) for all cases considered.

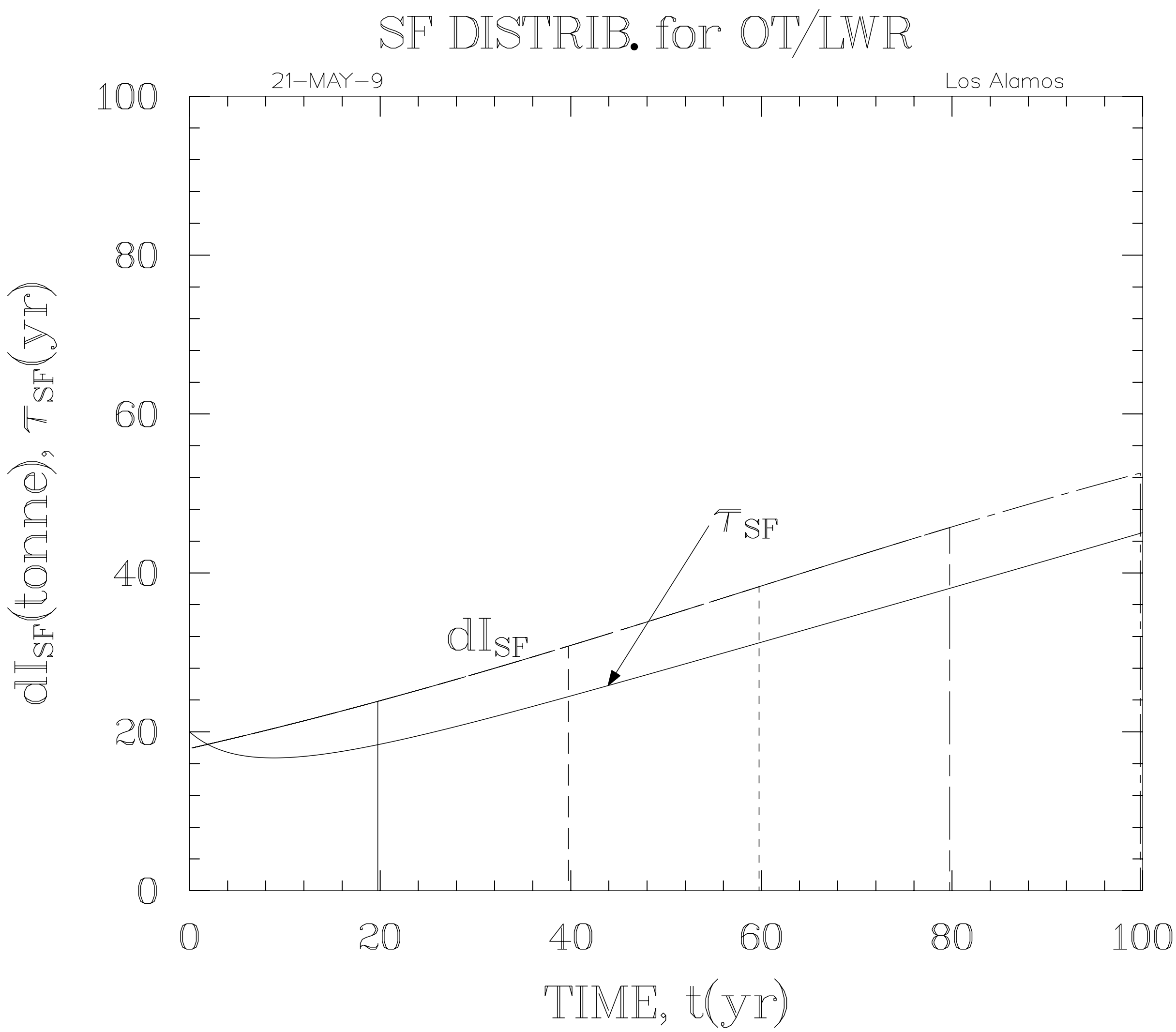


Figure 7. Evolution of spent-fuel age and creation distribution for the OT/LWR case.

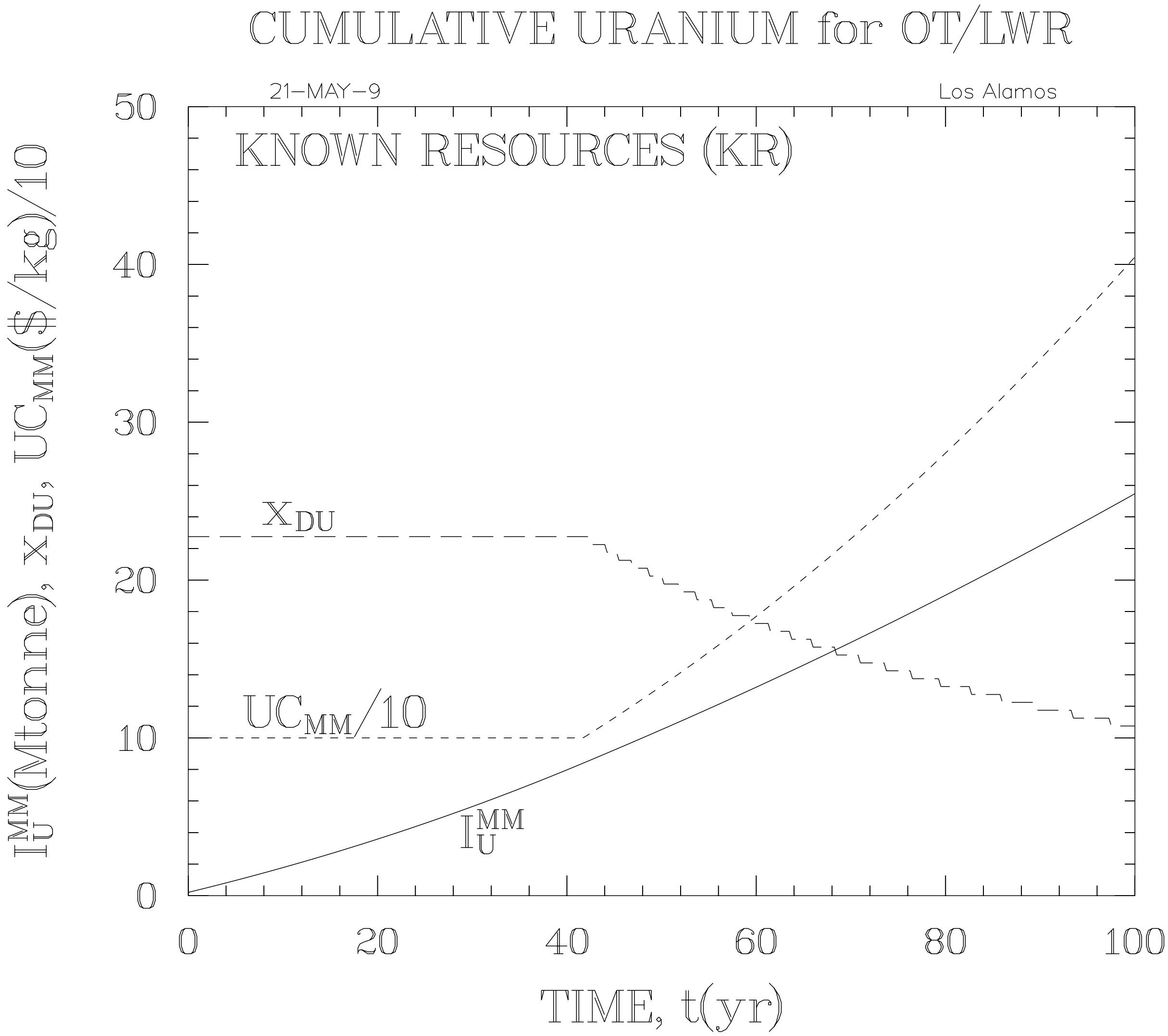


Figure 8. Time dependence of accumulated uranium usage, $I_U^{MM}$, optimal enrichment tailings composition, $x_{DU}$, and uranium unit cost, $UC_{MM}$, for the Known Resources (KR) scenario (Fig. 5) and the OT/LWR case.

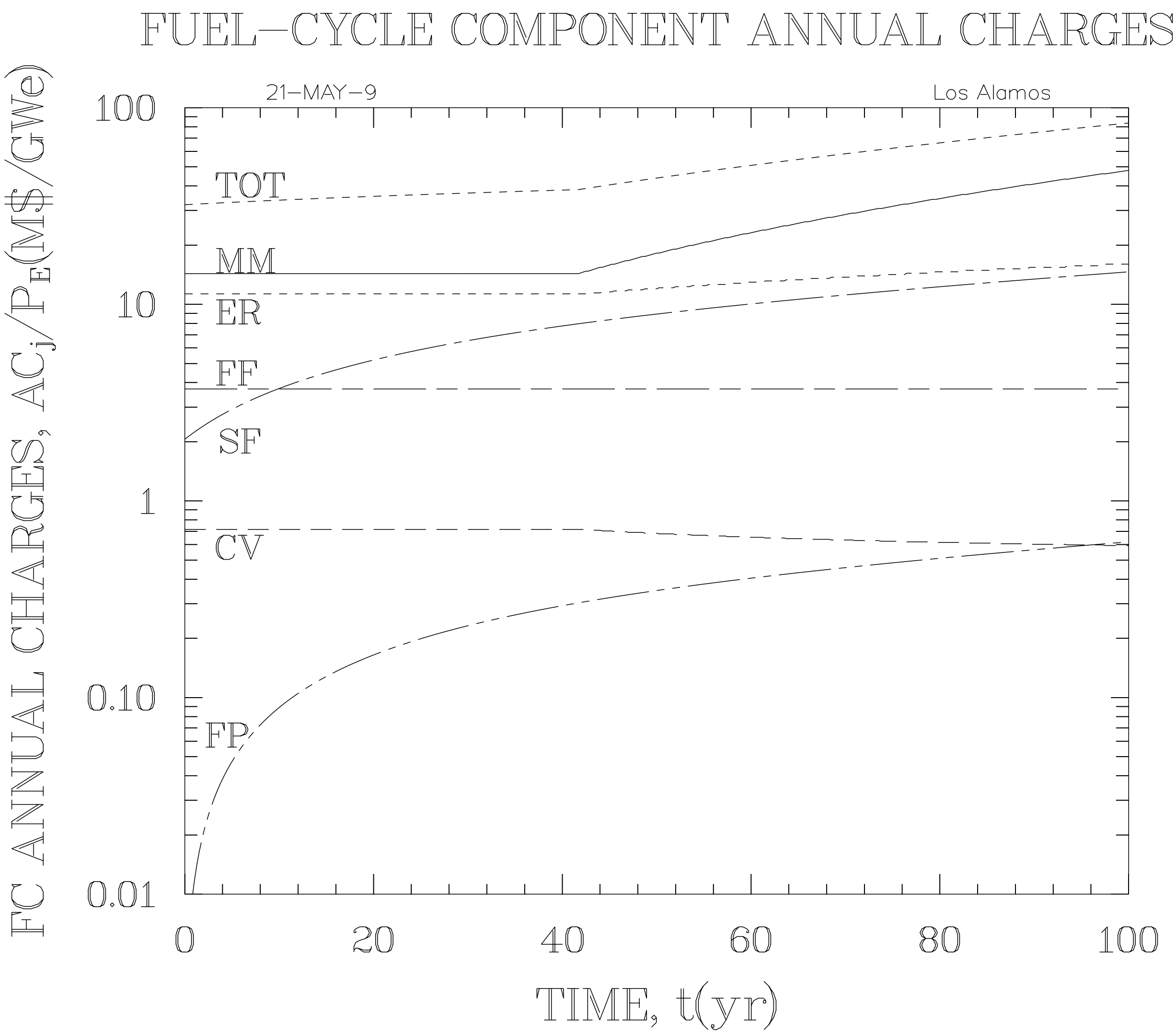


Figure 9. Normalized annual charges for key components of the nuclear fuel cycle for the OT/LWR case: MM = mining and milling; CV = $U_3O_8 \rightarrow UF_6$ conversion; ER = enrichment; FF = fuel fabrication; SF = spent-fuel storage; REP = reprocessing; FP = fission-product disposal; SPU = separated plutonium storage; CAP = capital cost differential between LWRs and FSBs (zeroed in this example); TOT = total. Charges related to REP, FP, and SPU are not incurred for the OT/LWR case.

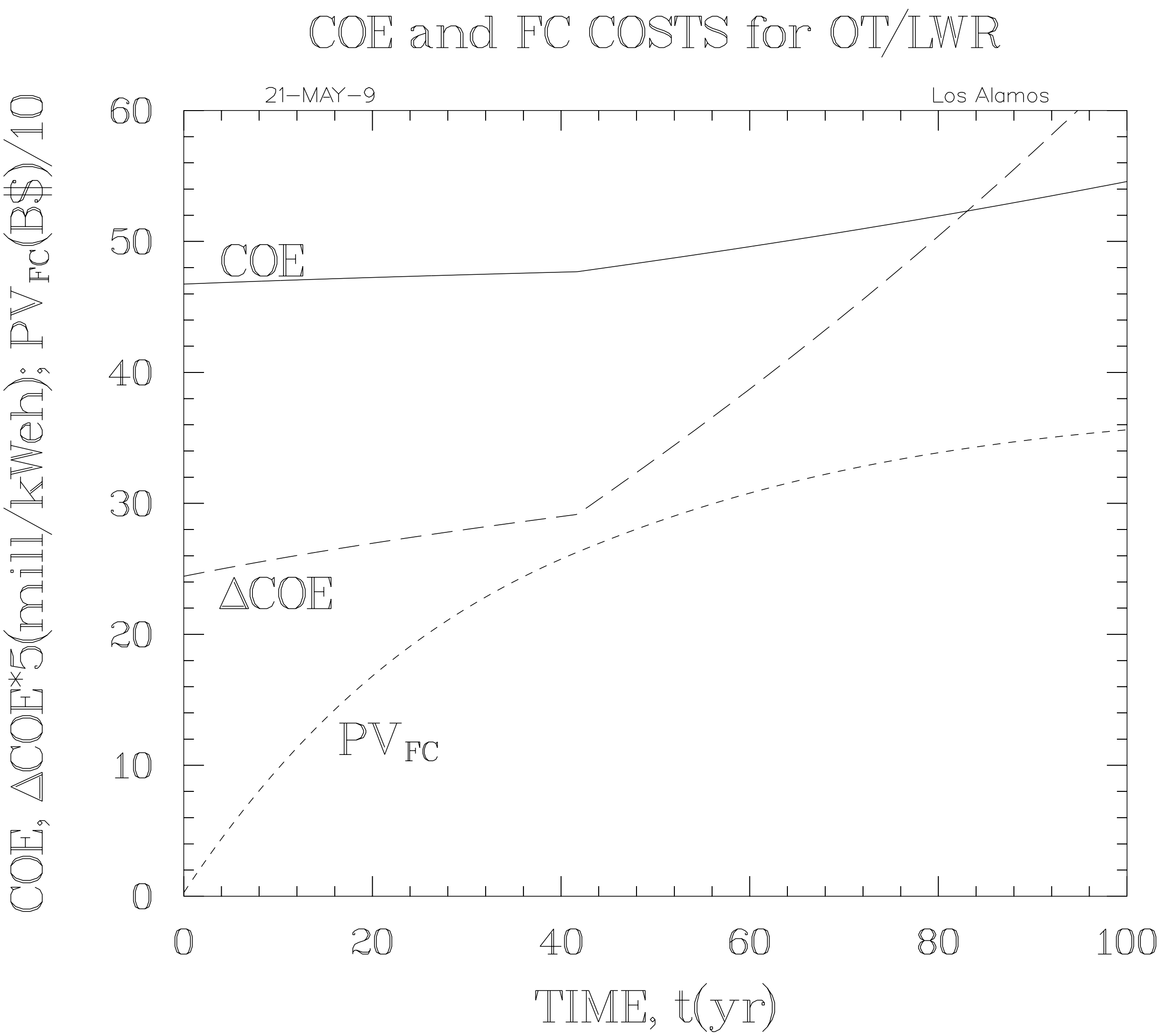


Figure 10. Time evolution of cost of electricity, COE(mill/kWeh), incremental COE related to the fuel cycle, ΔCOE(mill/kWeh), and present value of all fuel cycle charges evaluated over the time of the computation for a cost of money COM = 0.05 1/yr, for the OT/LWR case and uranium resources = KR (Fig. 5).

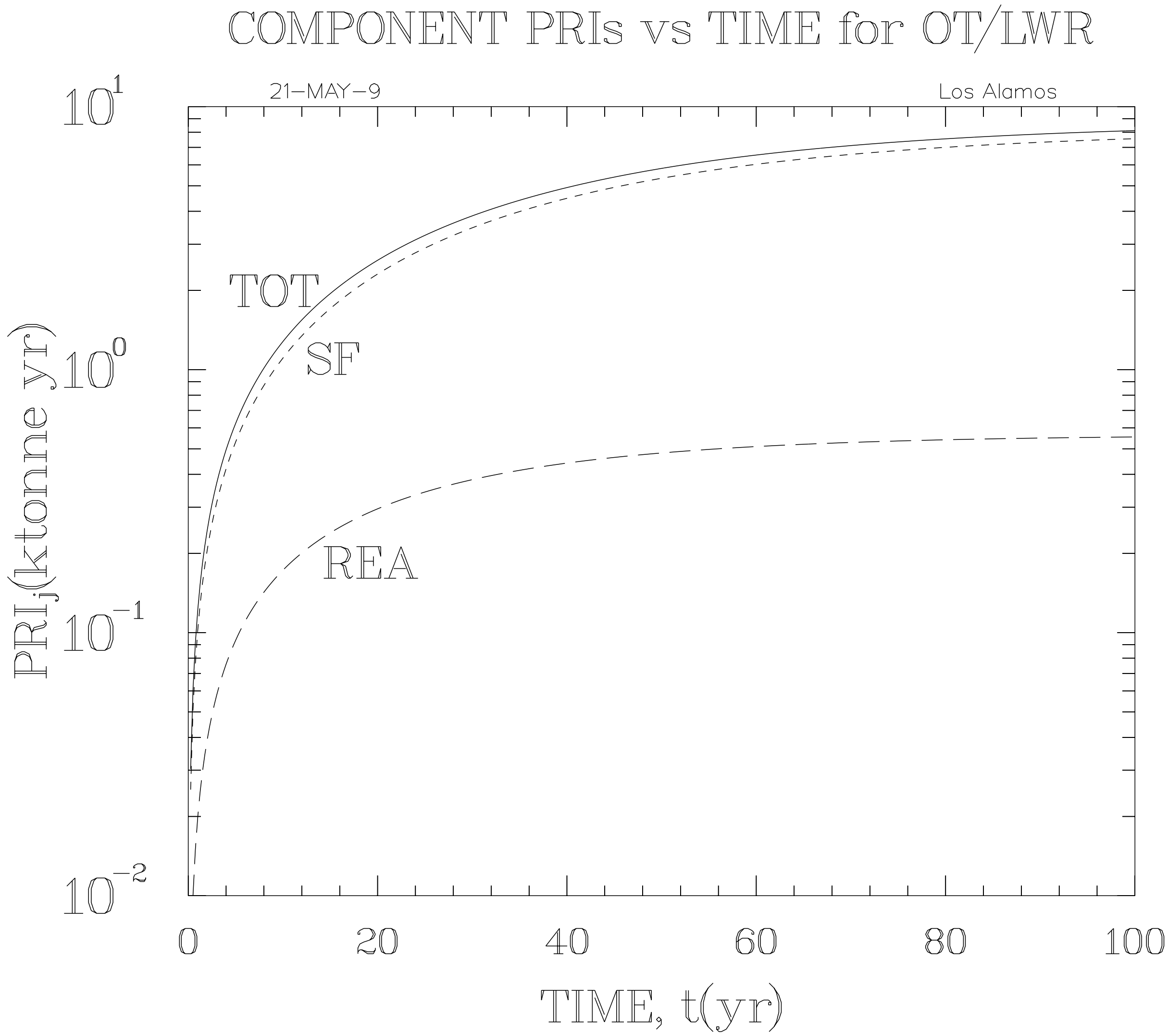


Figure 11. Time evolution of total and component proliferation risk indices, PRI(ktonne yr), for the OT/LWR case that discounts risk at a rate r = 0.05 1/yr using the weights listed in Tables I and II.

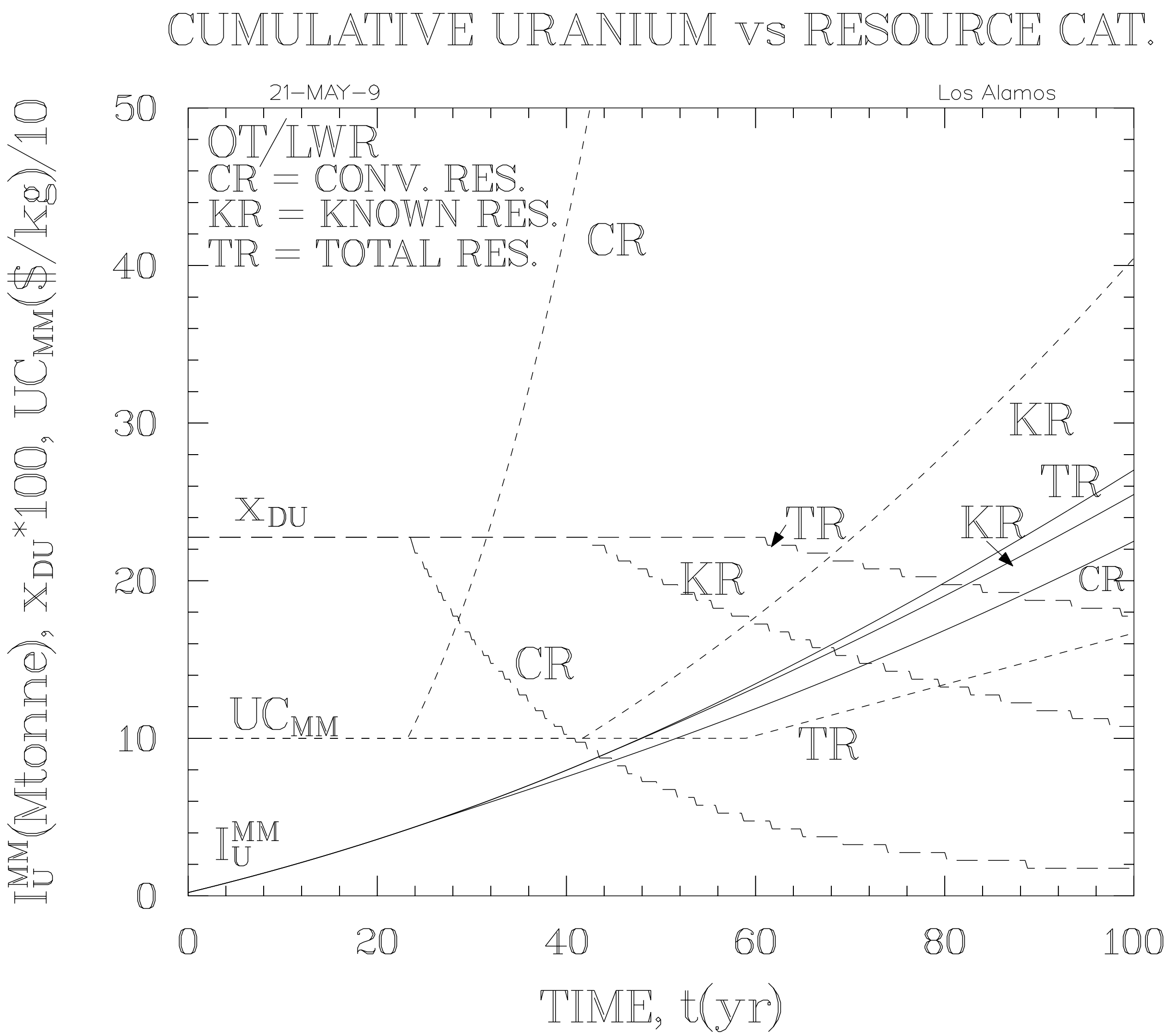


Figure 12. Cost impact of the range of uranium resource "realities" suggested on Fig. 5 for the OT/LWR case. Reflections of these uranium costs on COE and ΔCOE are given in comparison with the MOX/LWR case (Fig. 17).

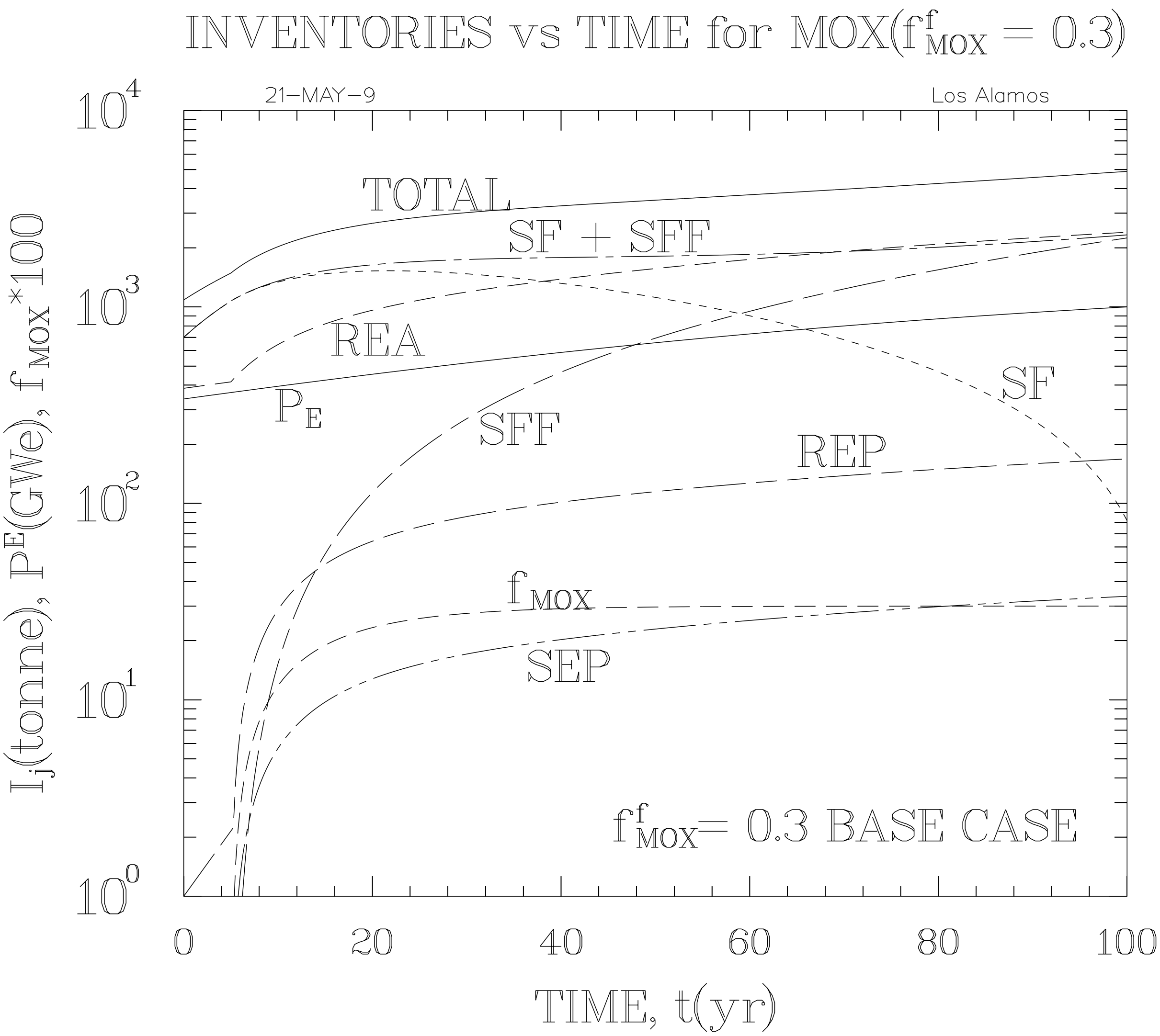


Figure 13. Time dependence of plutonium inventories for the MOX/LWR case when $f^f_{MOX}$ = 0.3. For this $N_{CYC}$ = 4 case, the spent-fuel inventory of LWR-recyclable plutonium, $I_{SF}$, decreases as the inventory of LWR-uncyclable plutonium, $I_{SFF}$, increases. Also shown is the time dependence of nuclear capacity, $P_E$, as given by Eq. (1) for all cases considered. The time dependence of $f_{MOX}$ is also shown.

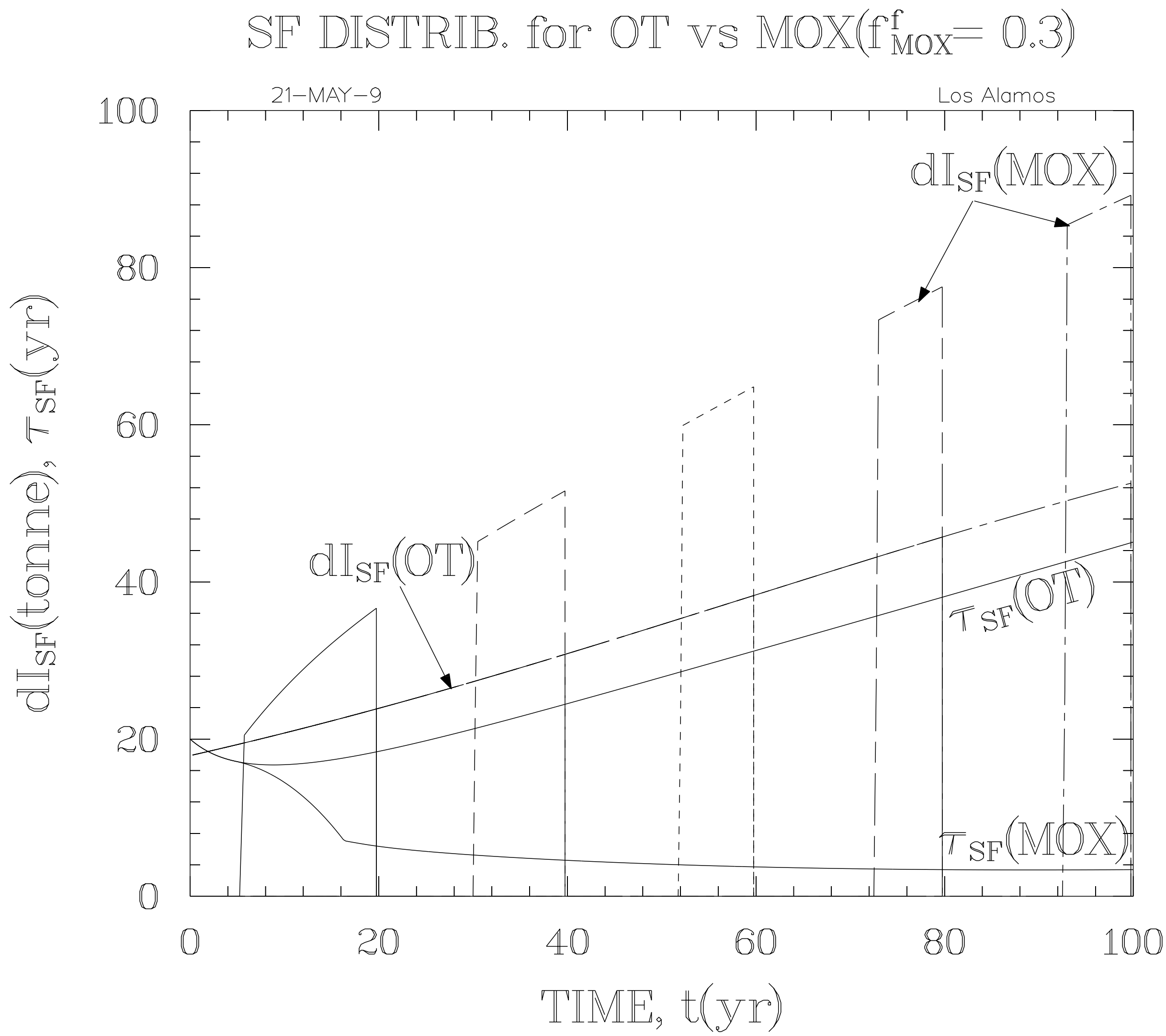


Figure 14. Evolution of spent-fuel age and creation distribution for the $f^{f}_{MOX}$ = 0.3 MOX/LWR case, showing a comparison with the OT/LWR case (Fig. 7).

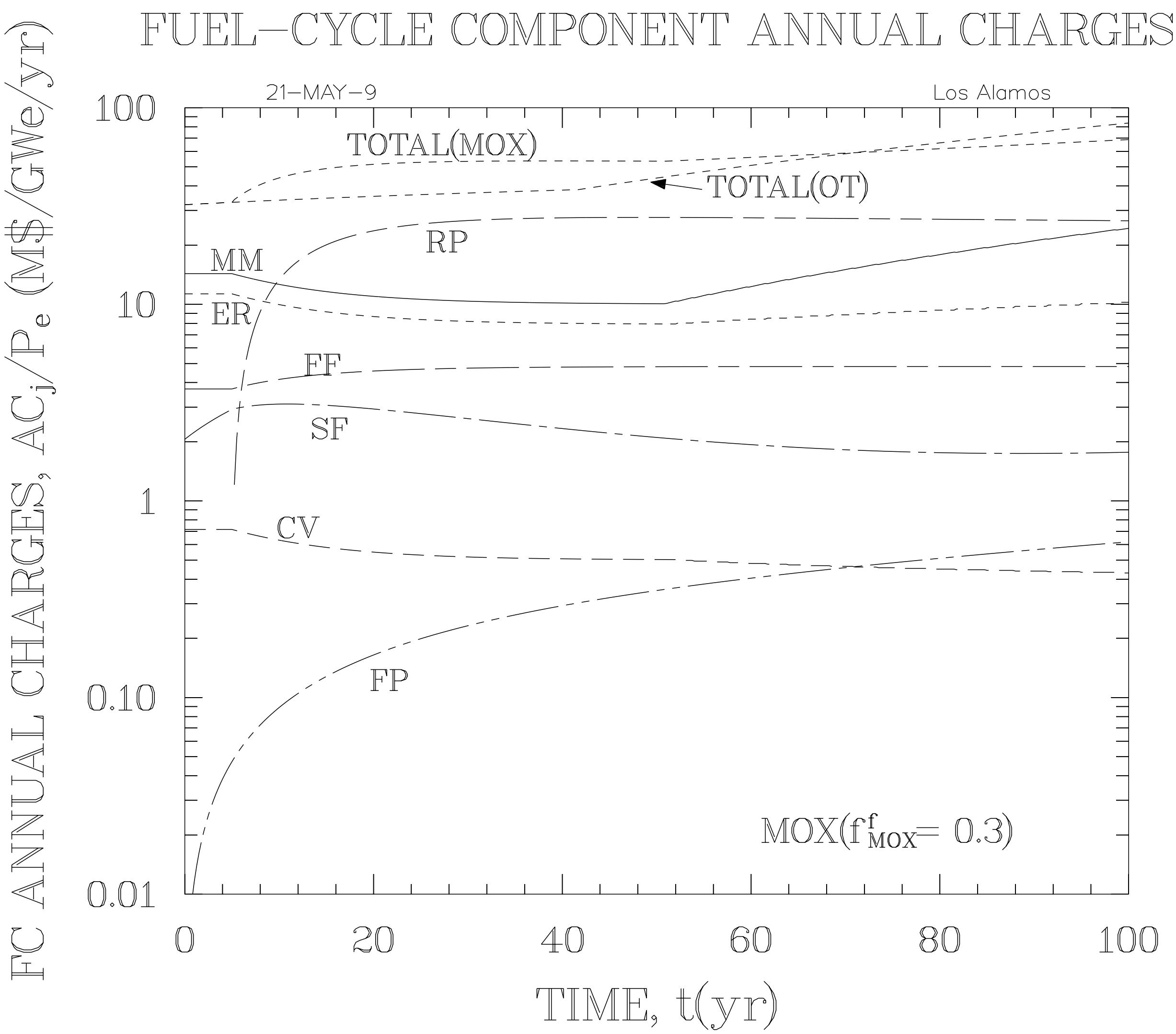


Figure 15. Normalized annual charges for key components of the nuclear fuel cycle for the $f^f_{MOX}$ = 0.3 MOX/LWR case; refer to Fig. 9 caption for notation. A comparison of the total annual charge associated with the fuel cycle with the OT/LWR case (Fig. 9) is also given.

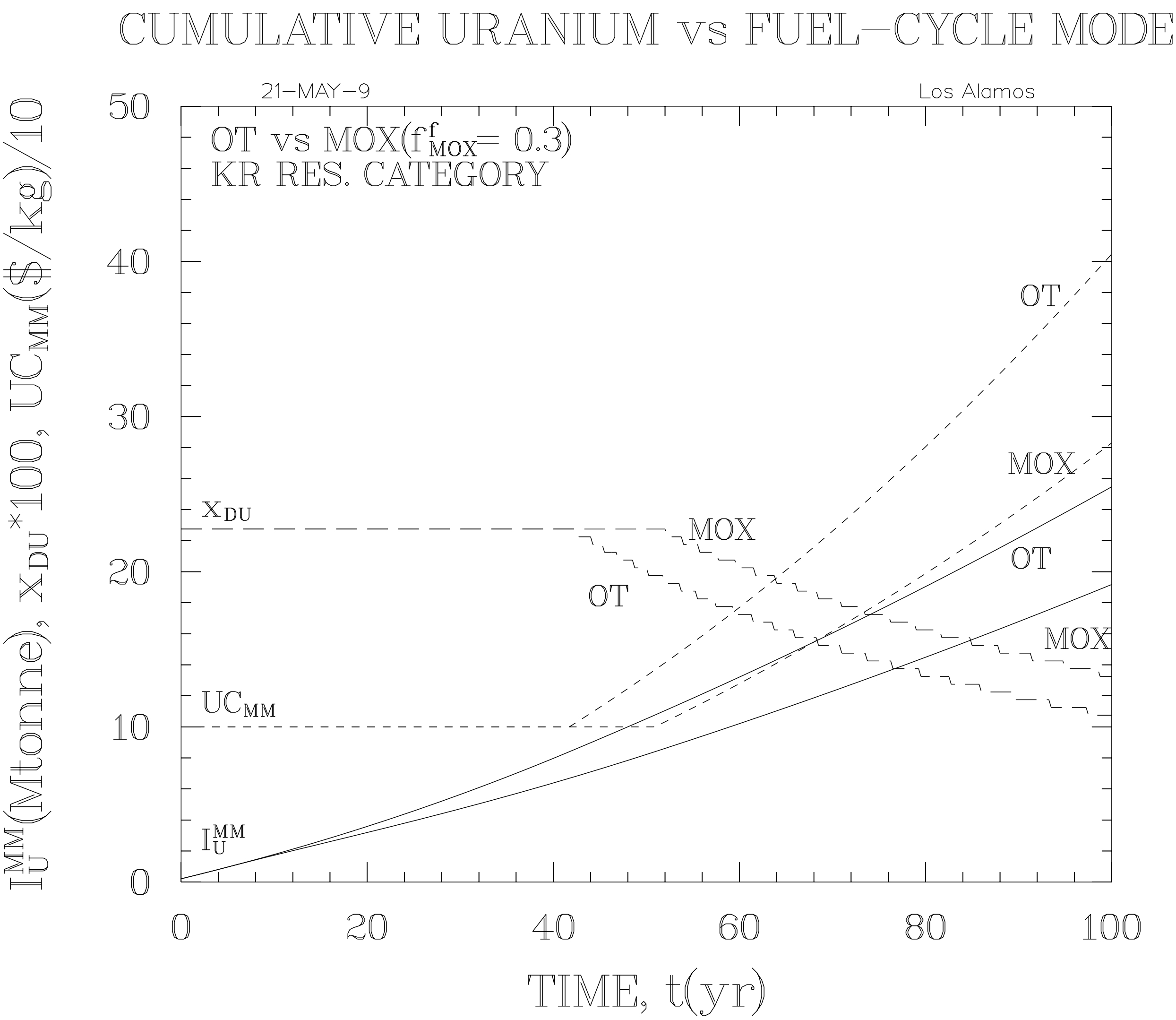


Figure 16. Cost impact of the KR (Known Resource) uranium resource category (Fig. 5), showing a comparison with the OT/LWR case depicted on Fig. 8, where the accumulated uranium usage is $I_U^{MM}$, the optimal enrichment tailings composition is $x_{DU}$, and uranium unit cost is $UC_{MM}$.

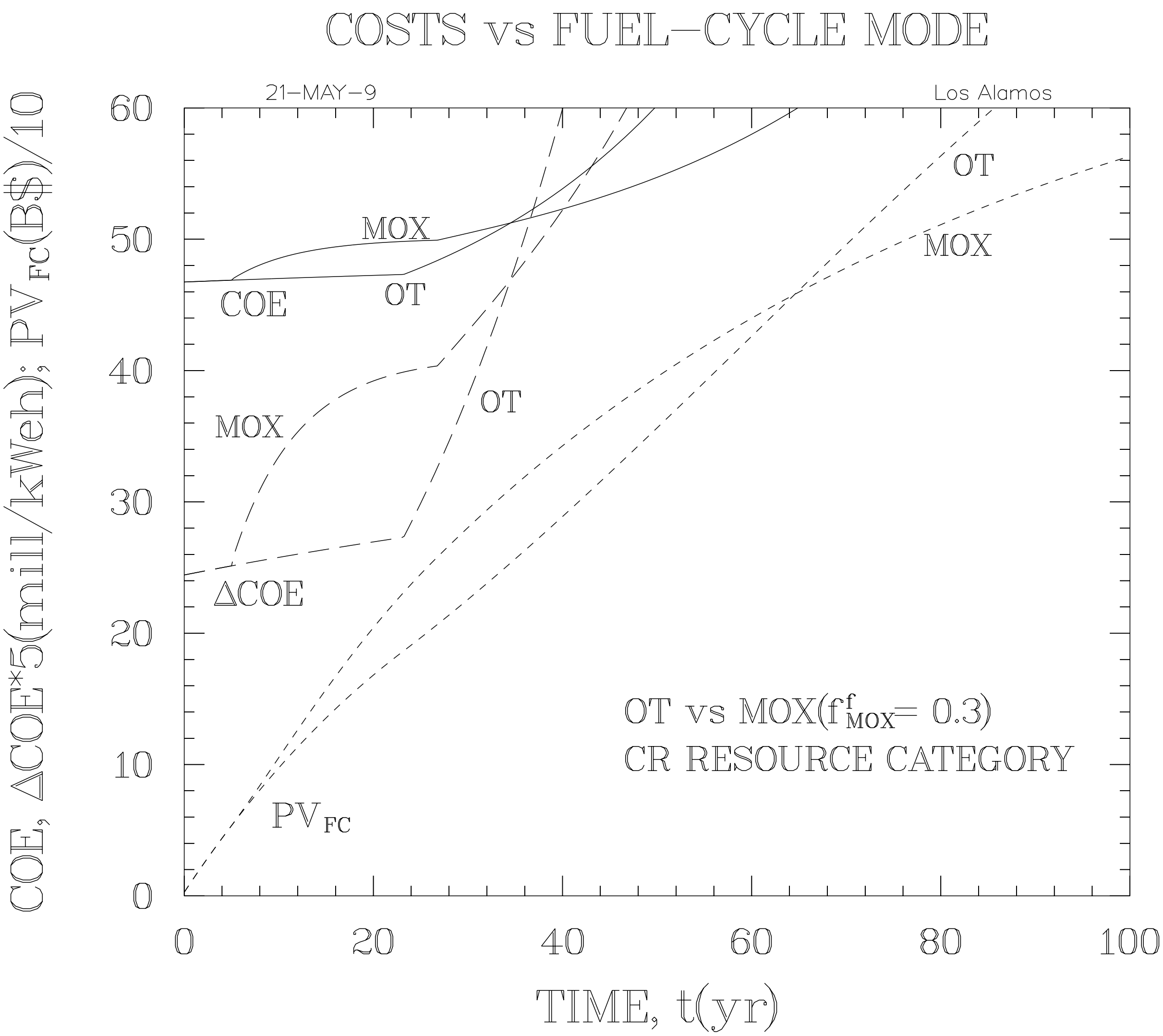


Figure 17A. Time evolution of cost of electricity, COE(mill/kWeh), incremental COE related to the fuel cycle, ΔCOE(mill/kWeh), and present value of all fuel cycle charges evaluated over the time of the computation for a cost of money COM = 0.05 1/yr, for the $f^{f}_{MOX}$ = 0.3 MOX/LWR case and the CR category of uranium resources (Fig. 5).

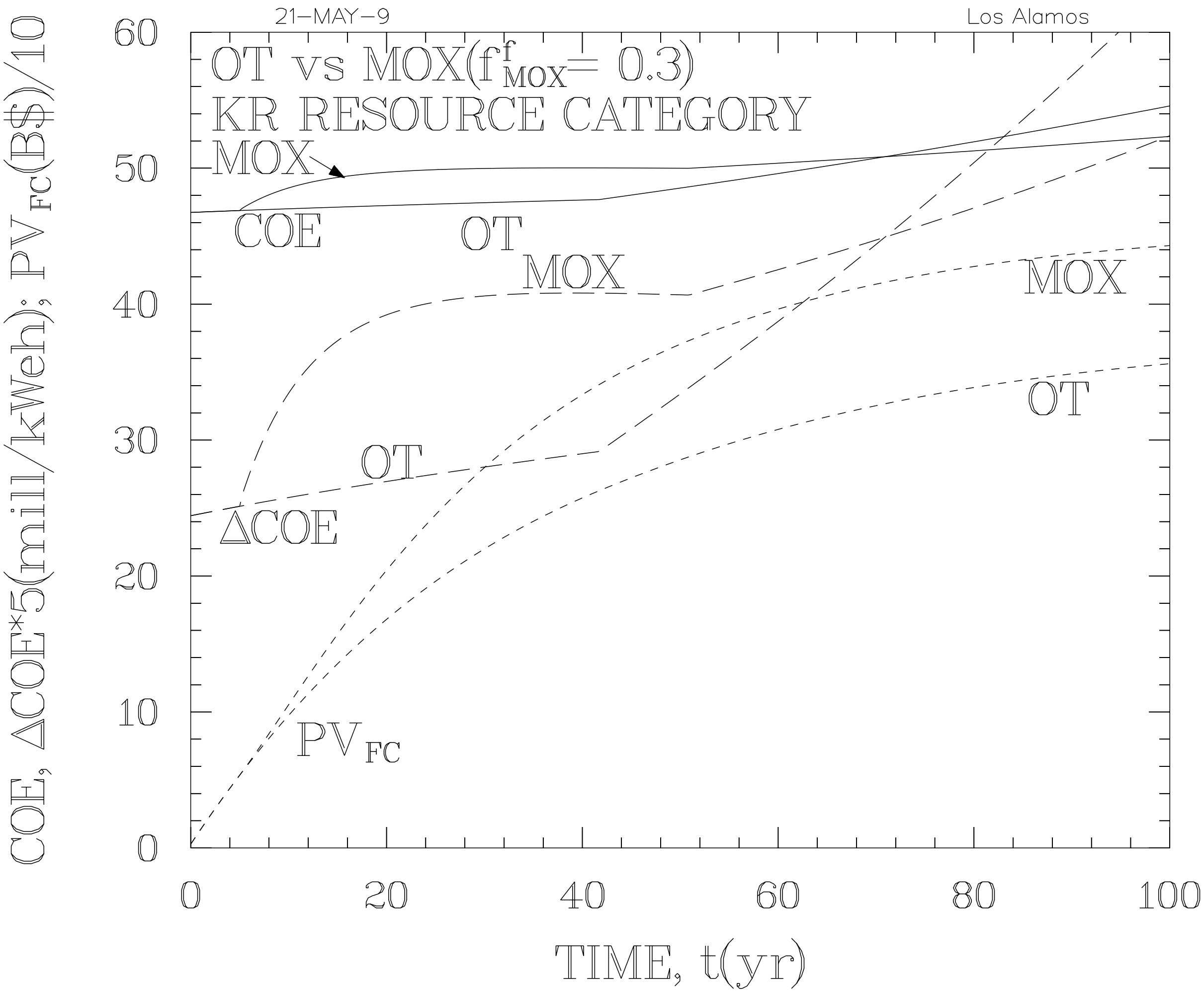


Figure 17B. Time evolution of cost of electricity, COE(mill/kWeh), incremental COE related to the fuel cycle, ΔCOE(mill/kWeh), and present value of all fuel cycle charges evaluated over the time of the computation for a cost of money COM = 0.05 1/yr, for the $f^f_{MOX}$ = 0.3 MOX/LWR case and the KR category of uranium resources (Fig. 5).

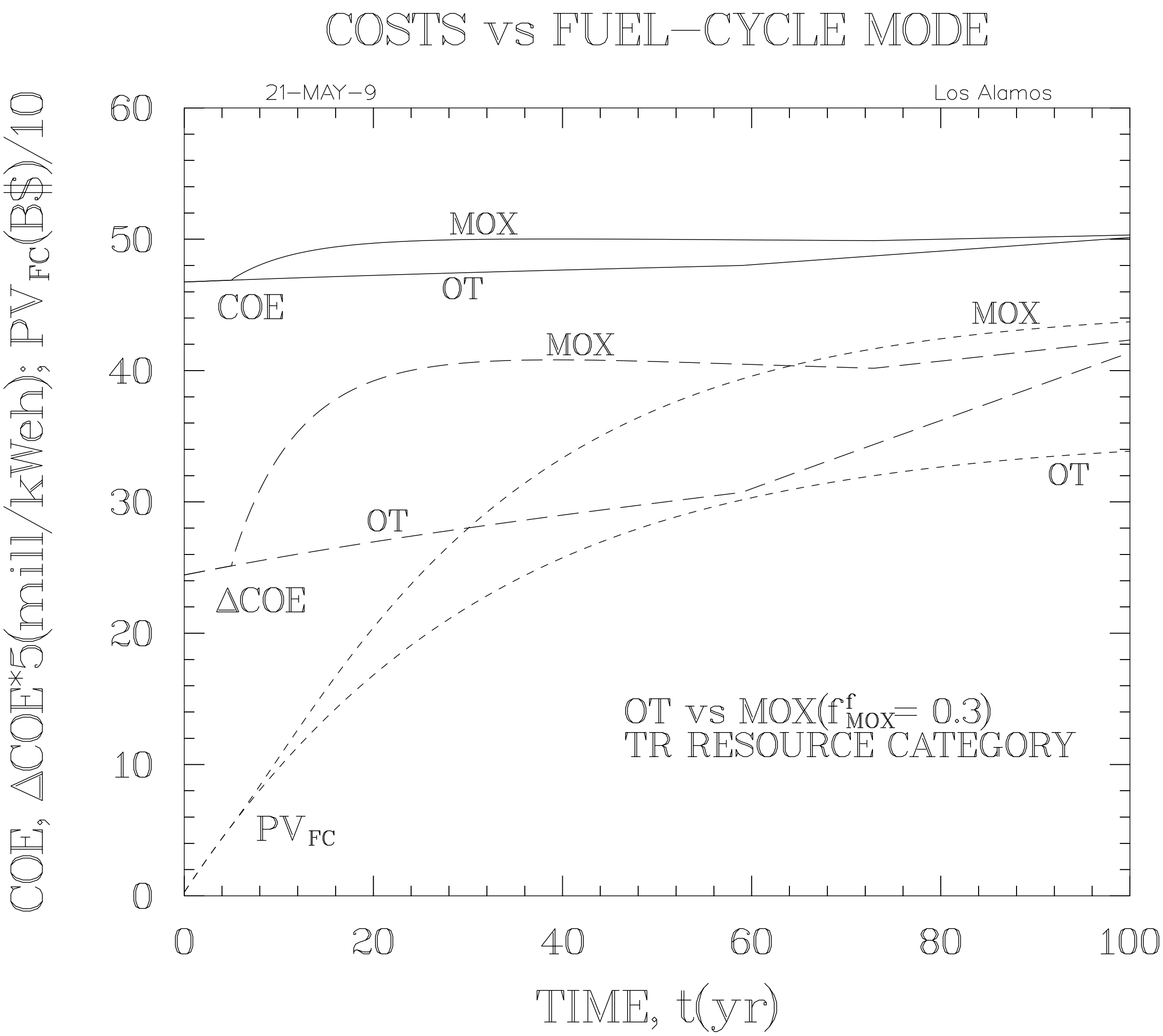


Figure 17C. Time evolution of cost of electricity, COE(mill/kWeh), incremental COE related to the fuel cycle, ΔCOE(mill/kWeh), and present value of all fuel cycle charges evaluated over the time of the computation for a cost of money COM = 0.05 1/yr, for the $f^{f}_{MOX}$ = 0.3 MOX/LWR case and the TR category of uranium resources (Fig. 5).

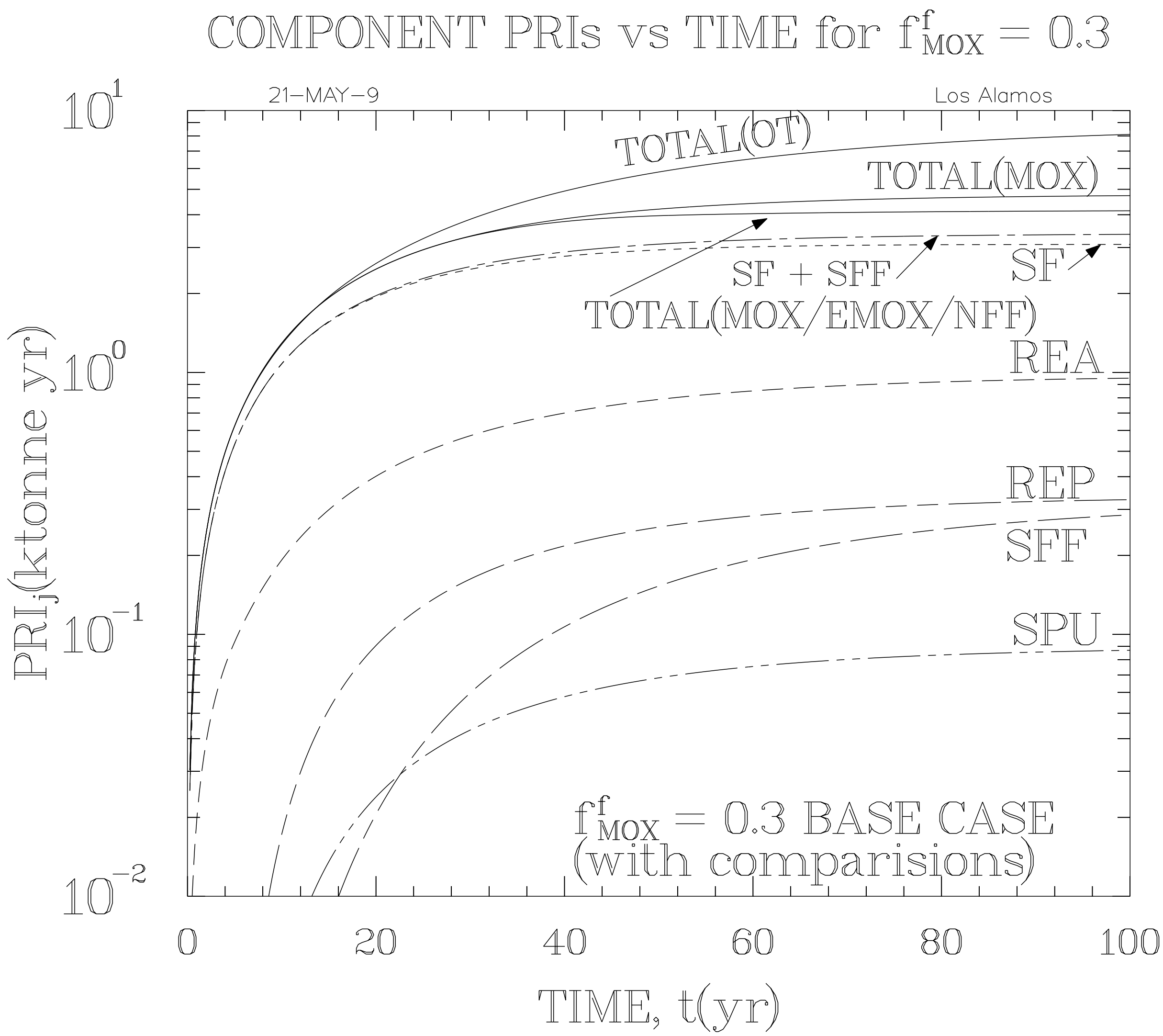


Figure 18. Time evolution of total and component proliferation risk indices, PRI(ktonne yr), for the $f^f_{MOX}$ = 0.3 MOX/LWR case that discounts risk at a rate r = 0.05 1/yr using the weights listed in Tables I and II. A comparison of the total PRI for the OT/LWR case reported on Fig. 11, as well as for a MOX/EMOX/NFF scenario reported in Sec. III.B.4, is given.

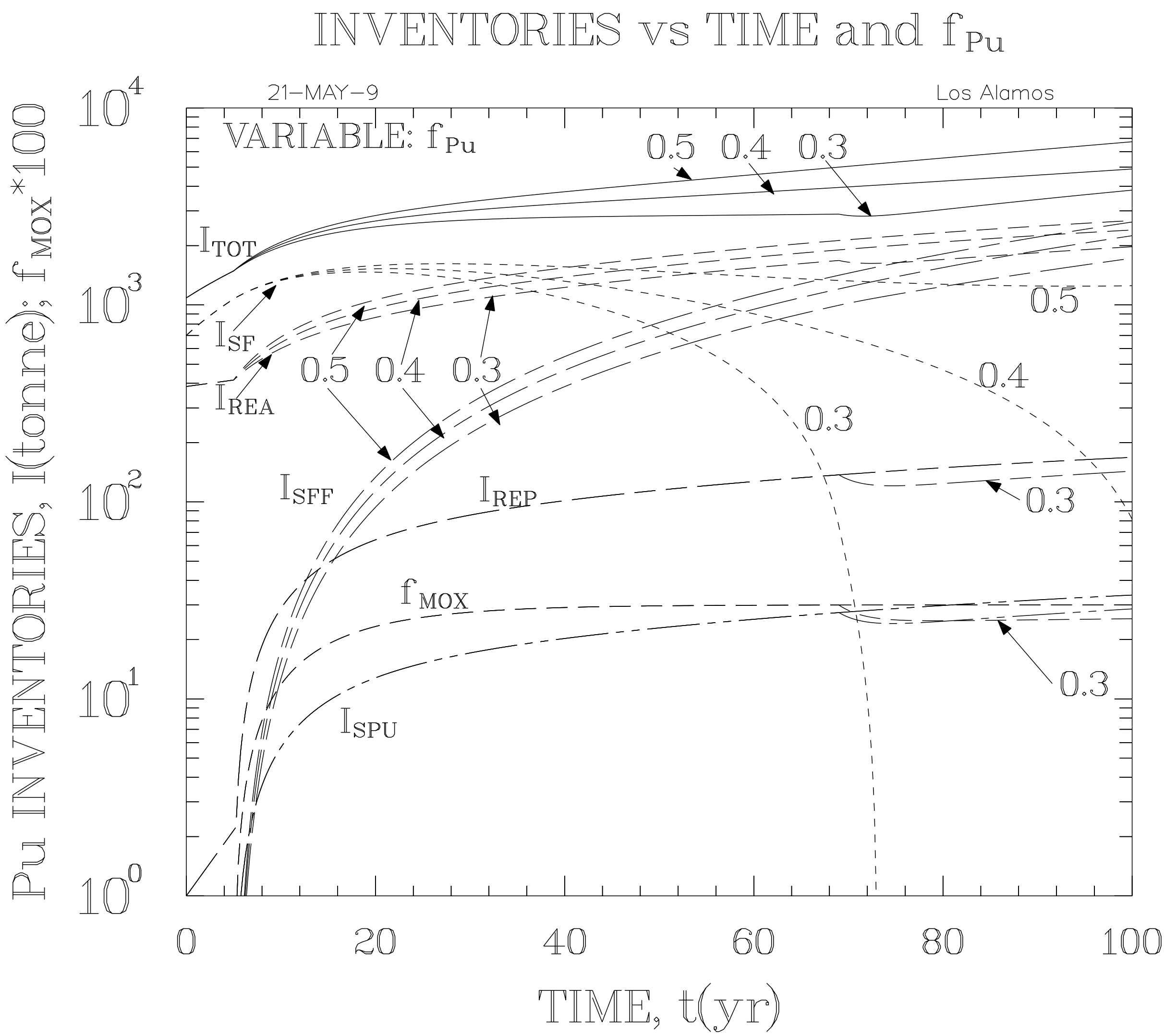


Figure 19. Time dependence of key plutonium inventories for the $f_{Pu}$ = 0.4 base case and for $f_{Pu}$ above and below the base-case value, with $f^f_{MOX}$ = 0.3, unless SF-plutonium inventory shortfalls occur.

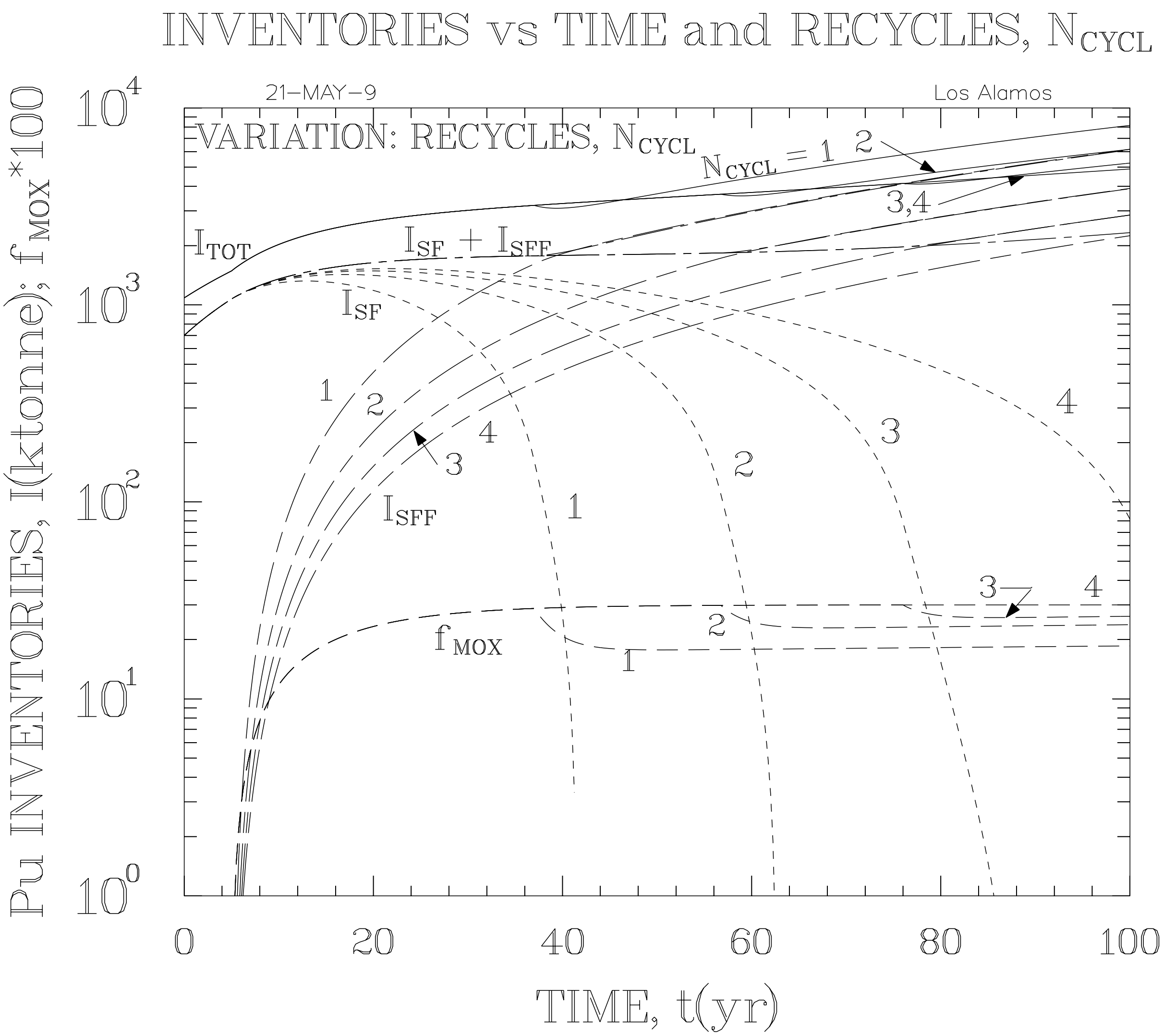


Figure 20. Time dependence of key plutonium inventories for the $N_{CYC}$ = 4 base case and for $N_{CYC}$ values below that used for the base case, with $f^f_{MOX}$ = 0.3, unless SF-plutonium inventory shortfalls occur.

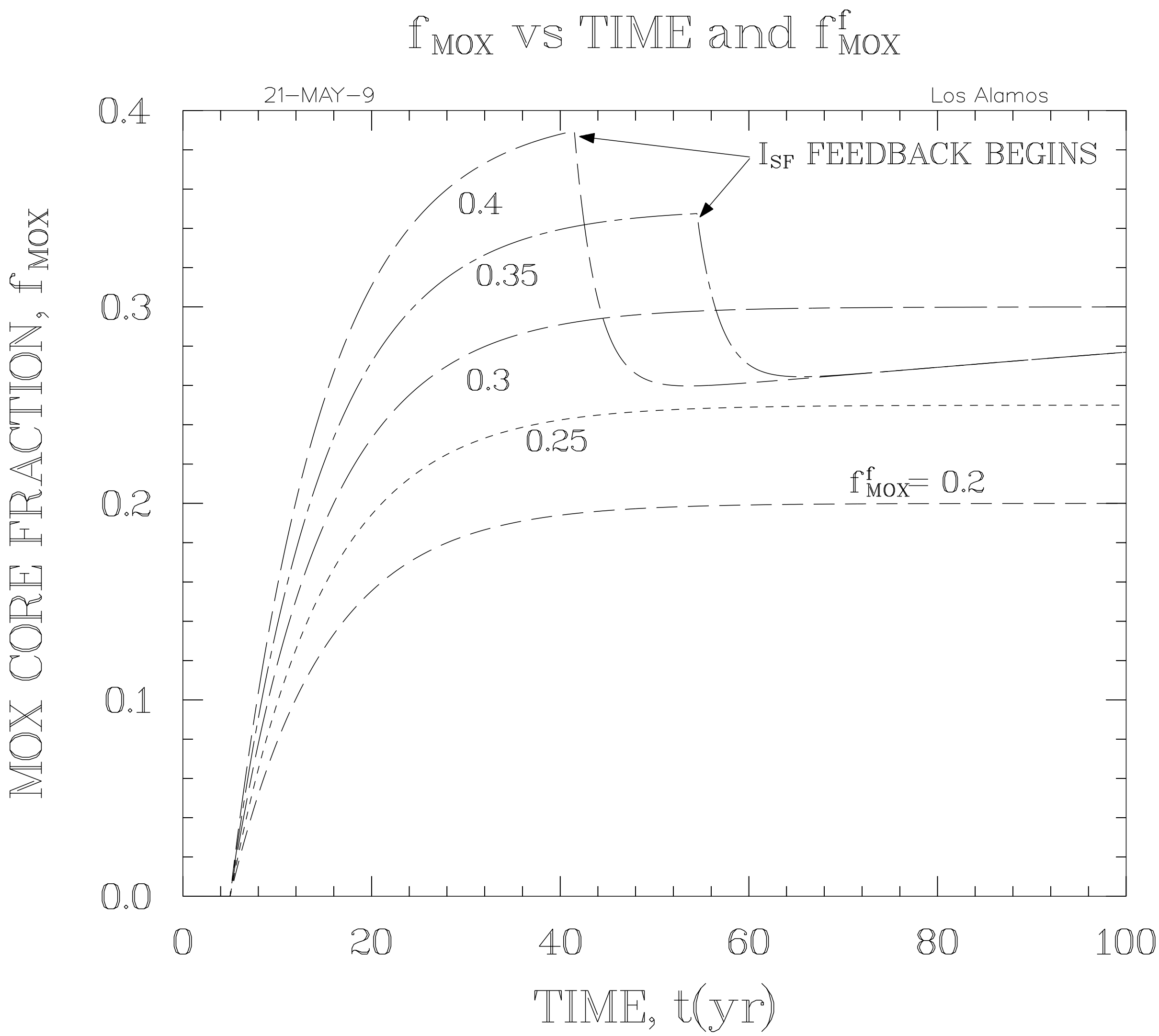


Figure 21. Time dependence of MOX core volume fraction as a function of asymptotic values, $f^f_{MOX}$, where the base case corresponds to $f^f_{MOX}$ = 0.3.

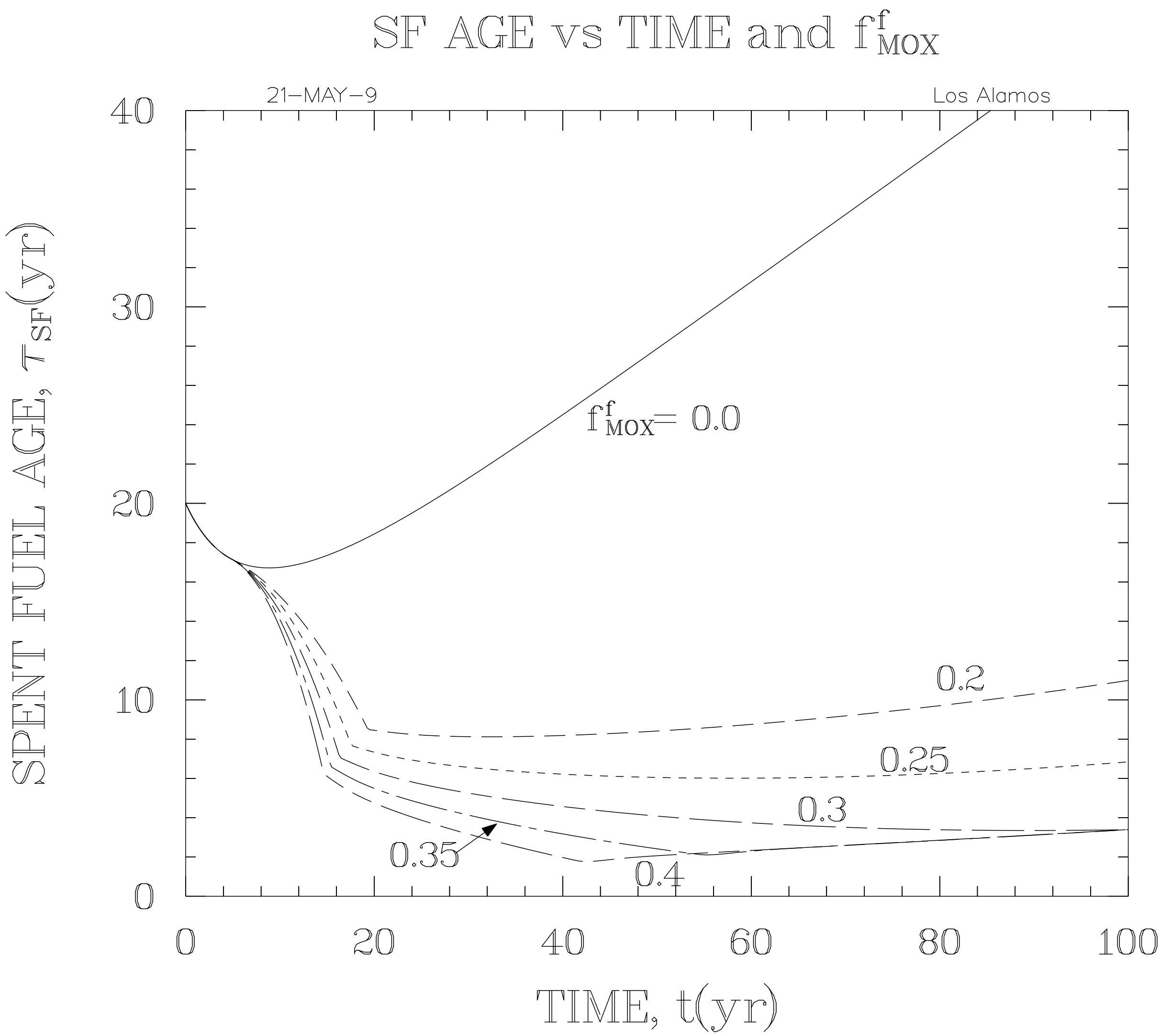


Figure 22. Time dependence of average spent-fuel age on asymptotic value of MOX core volume fraction for the cases depicted on Fig. 21; the OT/LWR case is designated by $f^f_{MOX}$ = 0.0.

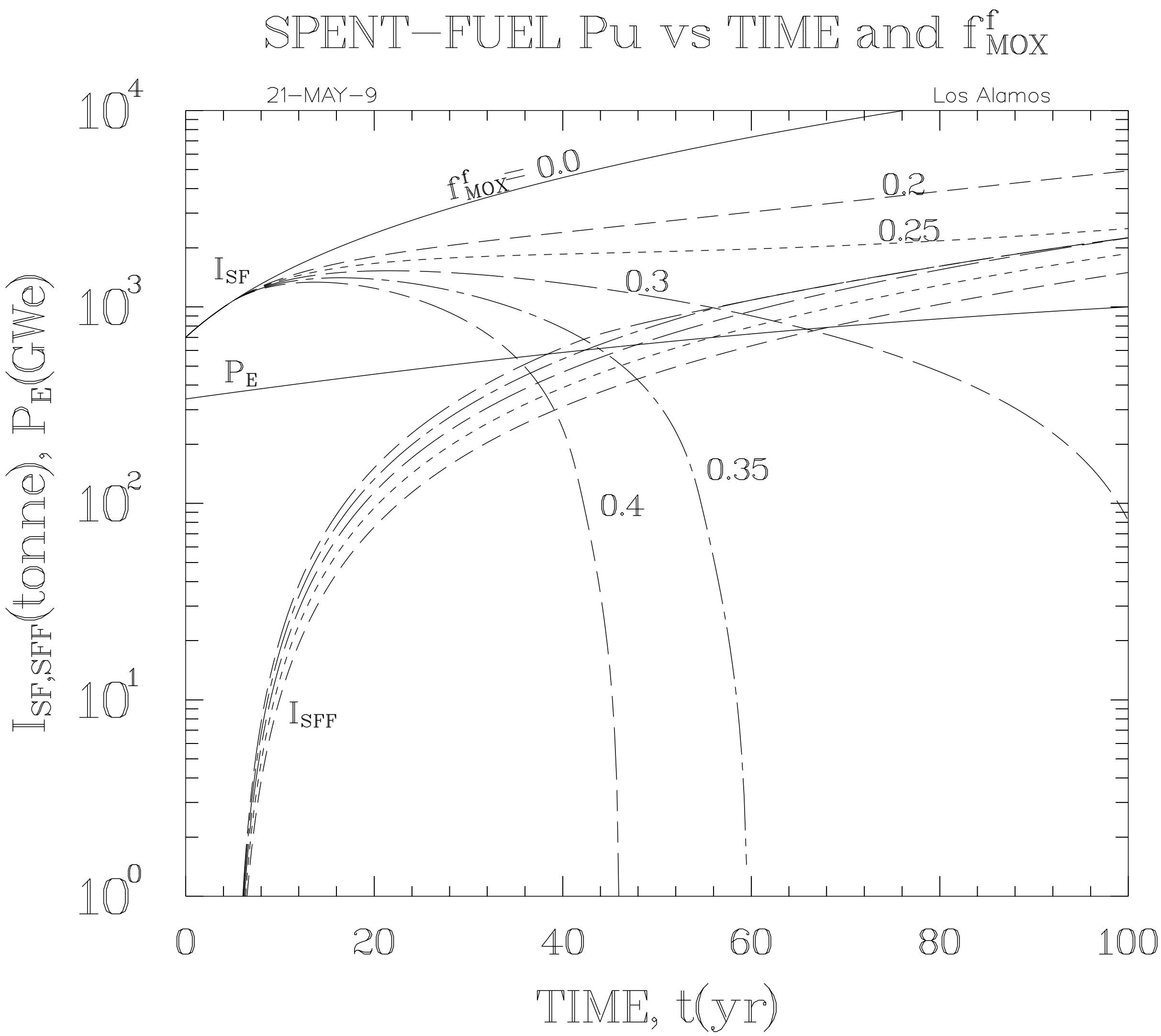


Figure 23A. Time dependence of key plutonium inventories for a range of asymptotic values of MOX core volume fraction for the cases depicted on Fig. 21; the OT/LWR case is designated by $f^f_{MOX}$ = 0.0; SF = LWR-recyclable and SFF = LWR-unusable plutonium in spent fuel.

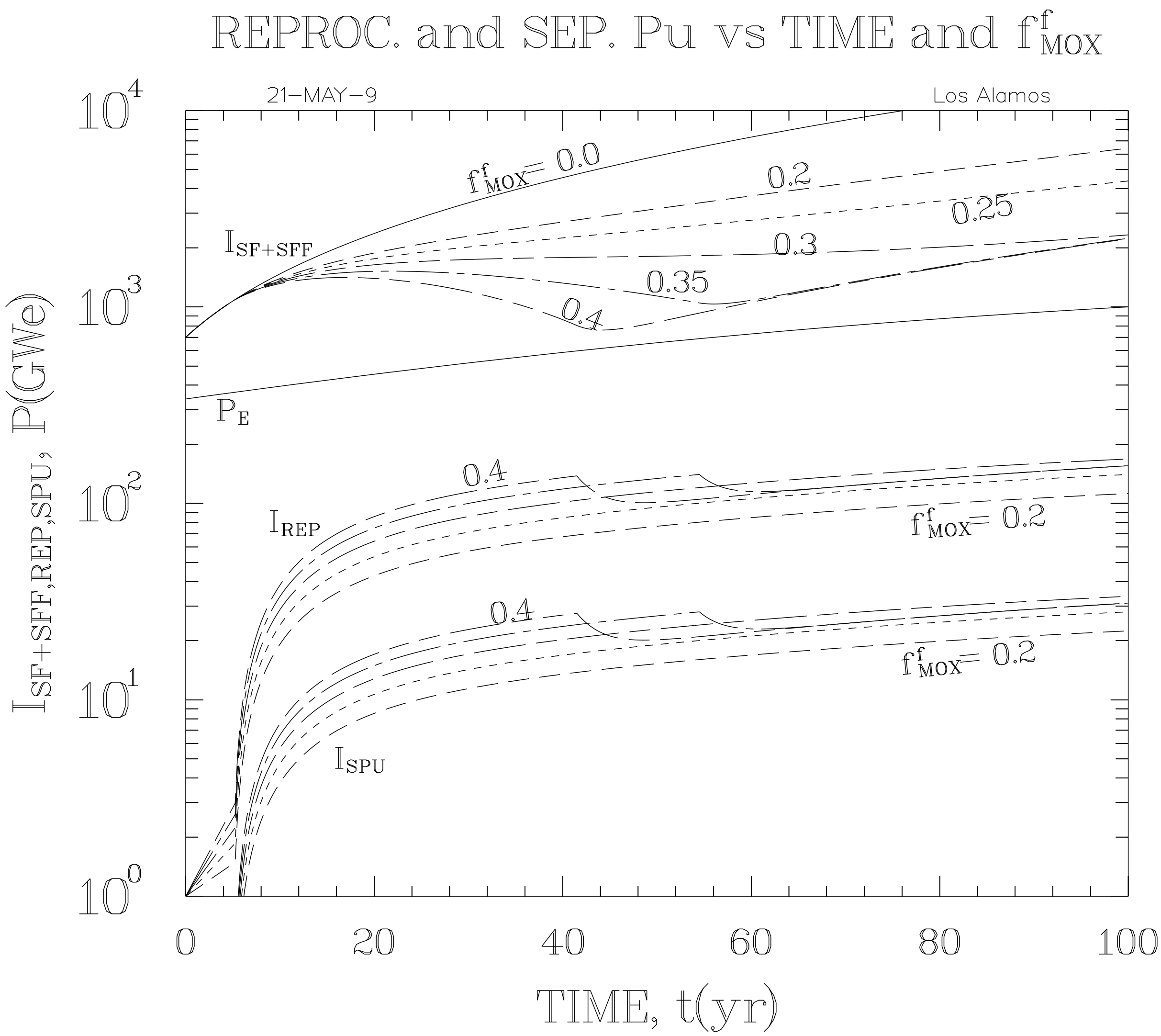


Figure 23B. Time dependence of key plutonium inventories for a range of asymptotic values of MOX core volume fraction for the cases depicted on Fig. 21; the OT/LWR case is designated by $f^f_{MOX}$ = 0.0; SF = LWR-recyclable and SFF = LWR-unusable in spent fuel; REP = reprocessing, and SPU = separated plutonium..

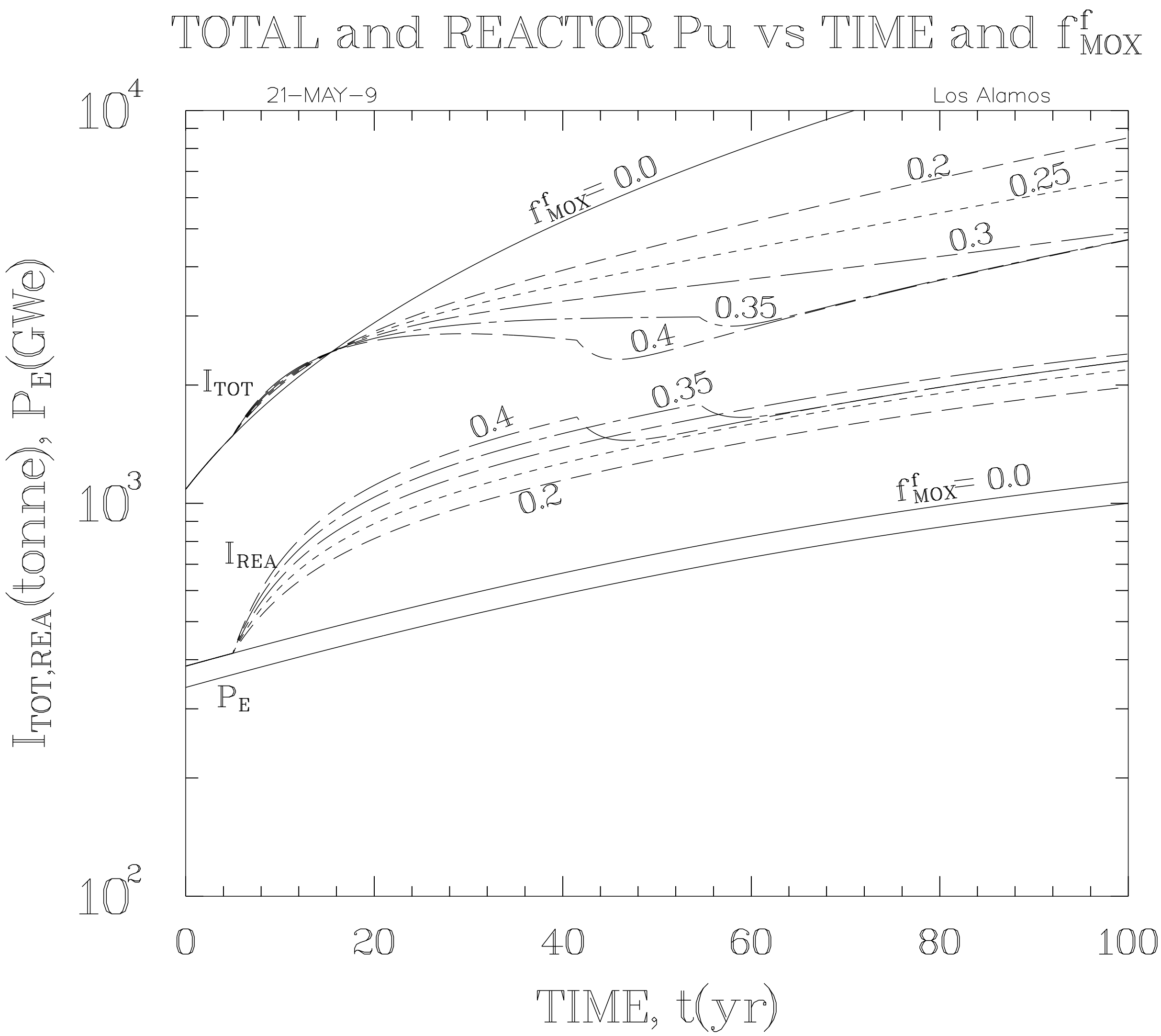


Figure 23C. Time dependence of key plutonium inventories for a range of asymptotic values of MOX core volume fraction for the cases depicted on Fig. 21; the OT/LWR case is designated by $f^f_{MOX}$ = 0.0; TOT = total and REA = reactor plutonium.

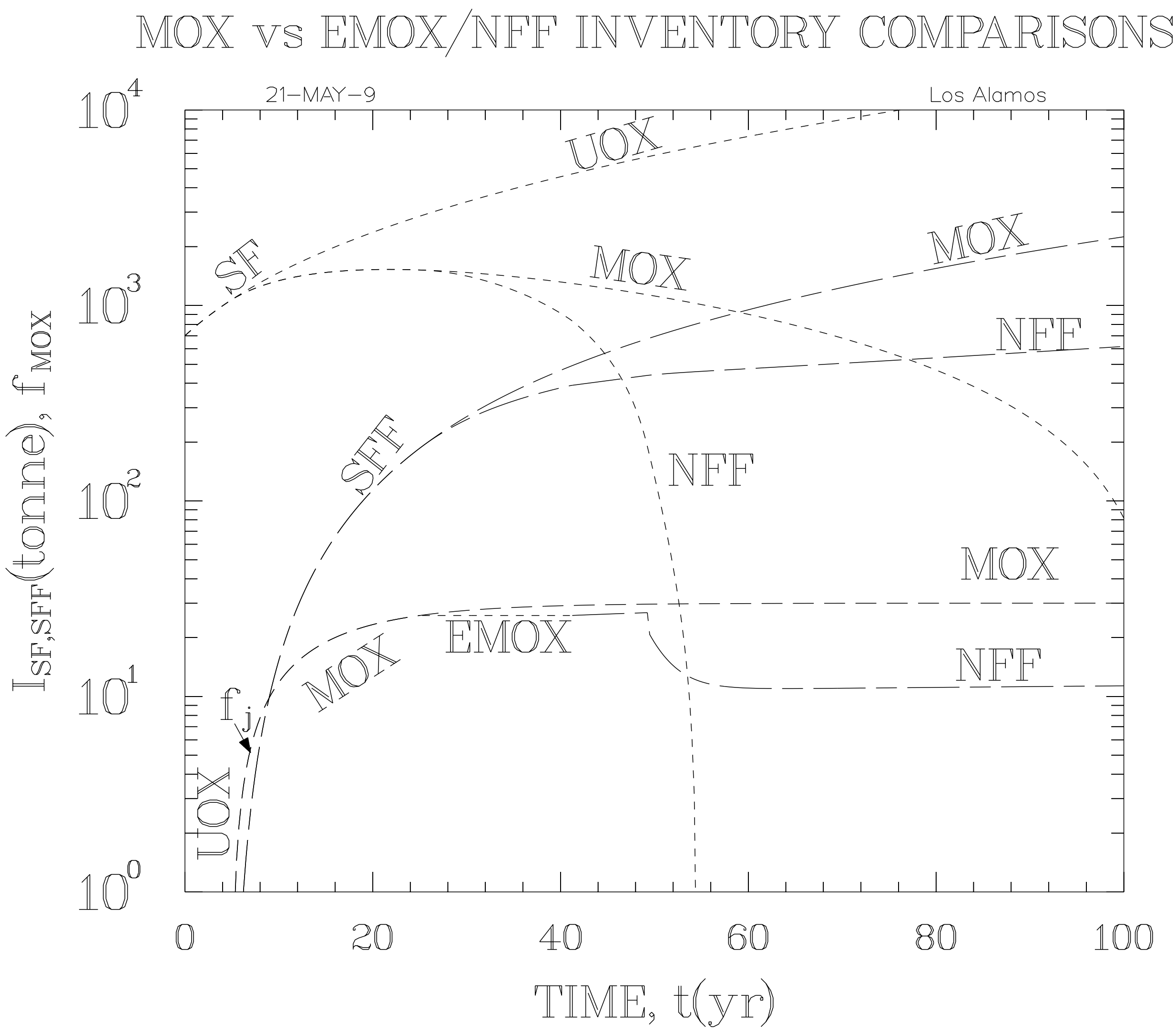


Figure 24A. Time dependence of key plutonium inventories for three fuel-cycle variations depicted on Fig. 3: a) OT/LWR (designated here as UOX); b) $f^{f}_{MOX}$ = 0.3 MOX/LWR (base case); and c) UOX/EMOX/NFF (as depicted by the full scenario given in Fig. 3); SF = LWR recyclable and SFF = LWR-unusable plutonium in spent fuel.

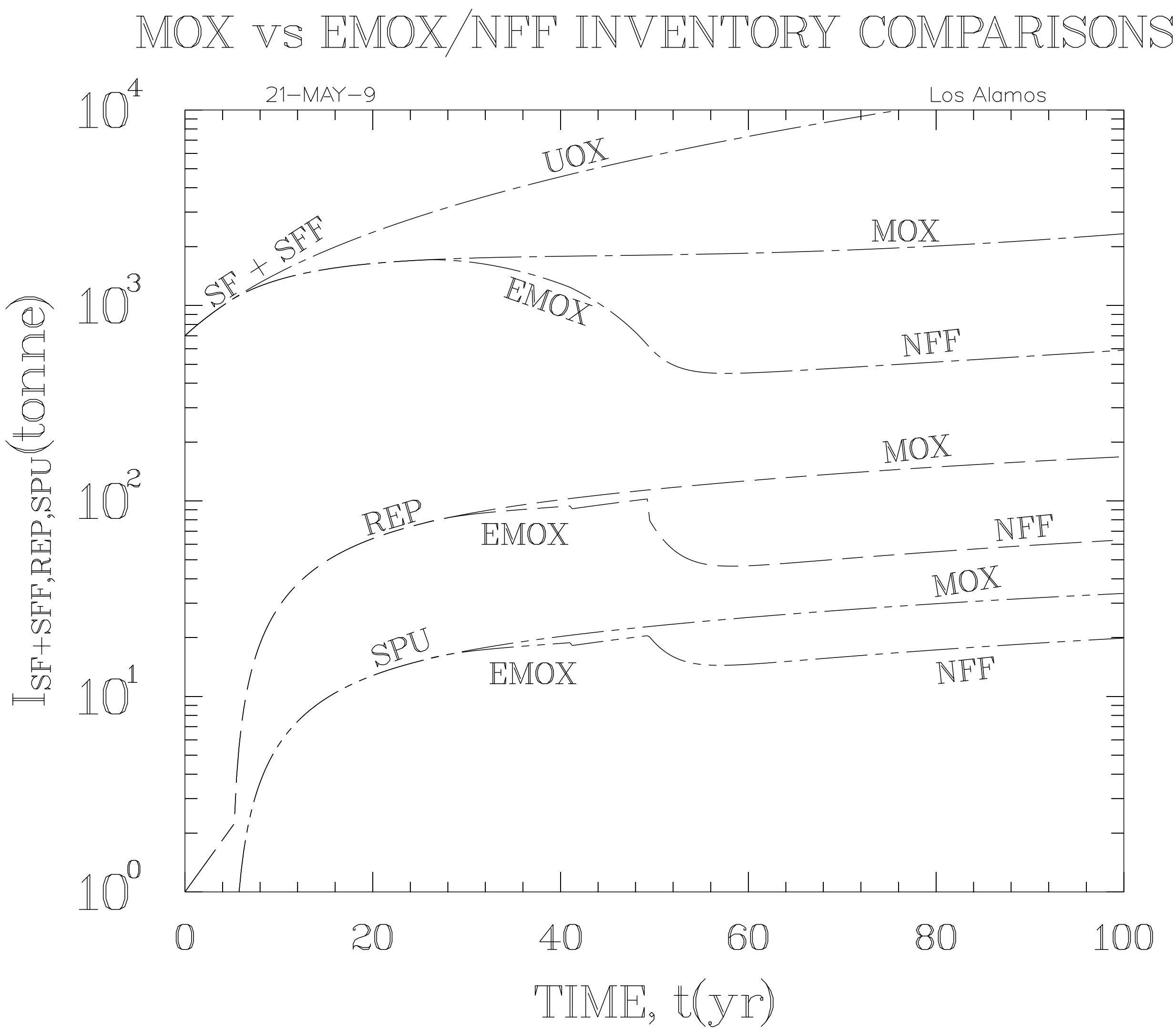


Figure 24B. Time dependence of key plutonium inventories for three fuel-cycle variations depicted on Fig. 3: a) OT/LWR (designated here as UOX); b) $f^{f}_{MOX}$ = 0.3 MOX/LWR (base case); and c) UOX/EMOX/NFF (as depicted by the full scenario given in Fig. 3); SF = LWR-recyclable and SFF = LWR-unusable plutonium in spent fuel, and SPU = separated plutonium.

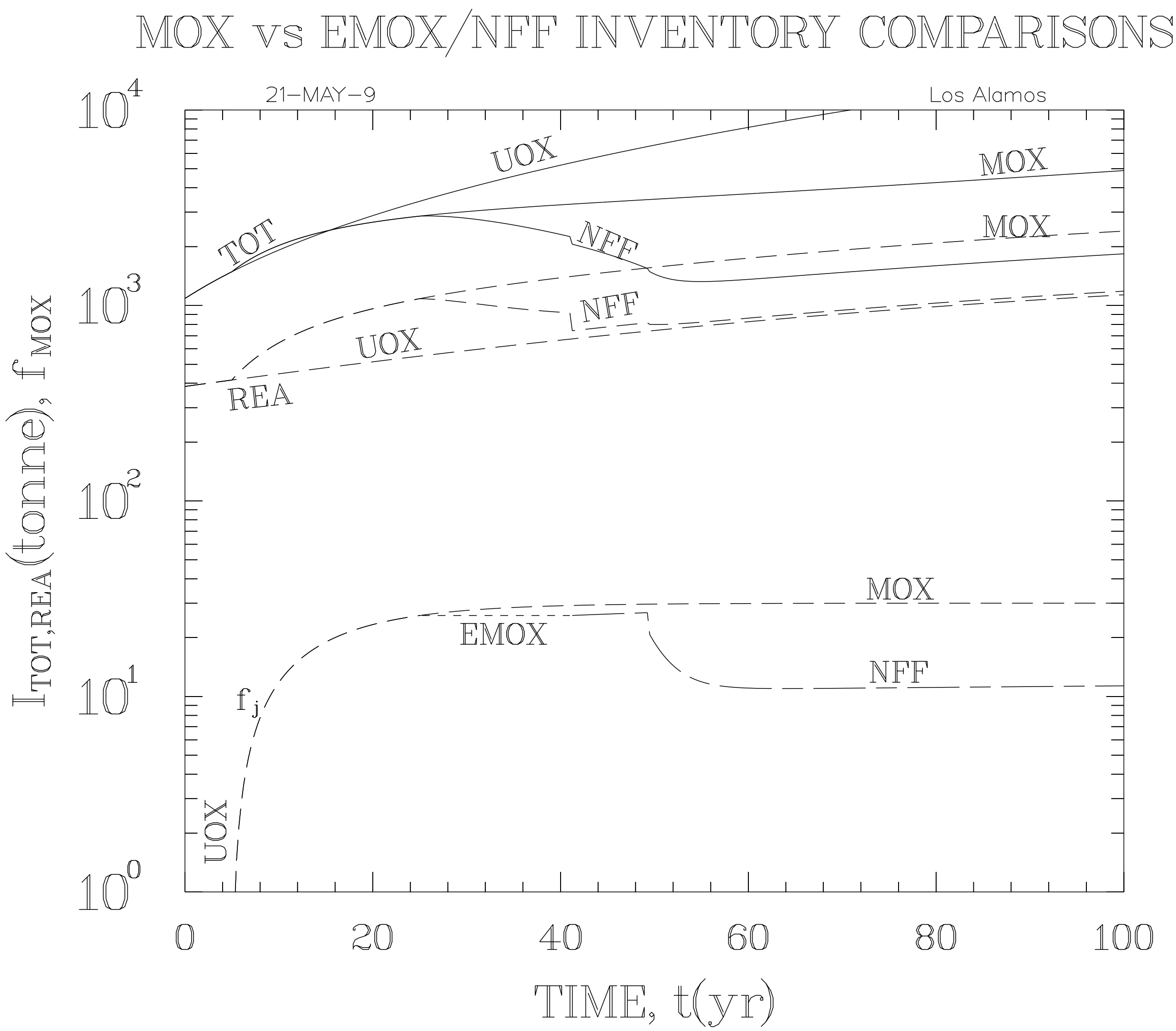


Figure 24C. Time dependence of key plutonium inventories for three fuel-cycle variations depicted on Fig. 3: a) OT/LWR (designated here as UOX); b) $f^{f}_{MOX}$ = 0.3 MOX/LWR (base case); and c) UOX/EMOX/NFF (as depicted by the full scenario given in Fig. 3); TOT = total and REA =- reactor plutonium.

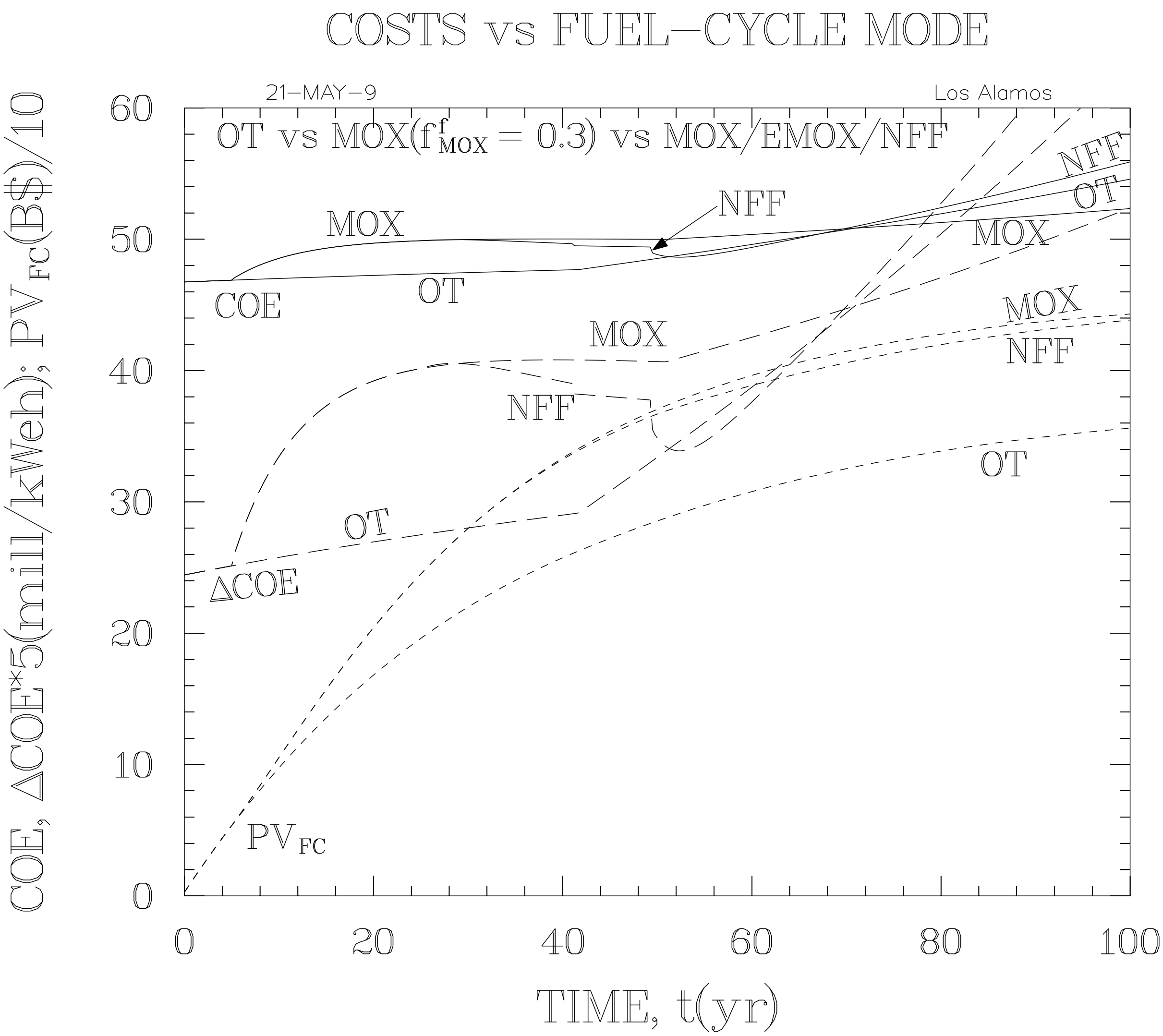


Figure 25. Time evolution of cost of electricity, COE(mill/kWeh), incremental COE related to the fuel cycle, ΔCOE(mill/kWeh), and present value of all fuel cycle charges evaluated over the time of the computation for a cost of money COM = 0.05 1/yr, for: a) the OT/LWR case; b) the $f^f_{MOX}$ = 0.3 MOX/LWR base case; and c) the UOX/EMOX/NFF case, as depicted by the full scenario given in Fig. 3.

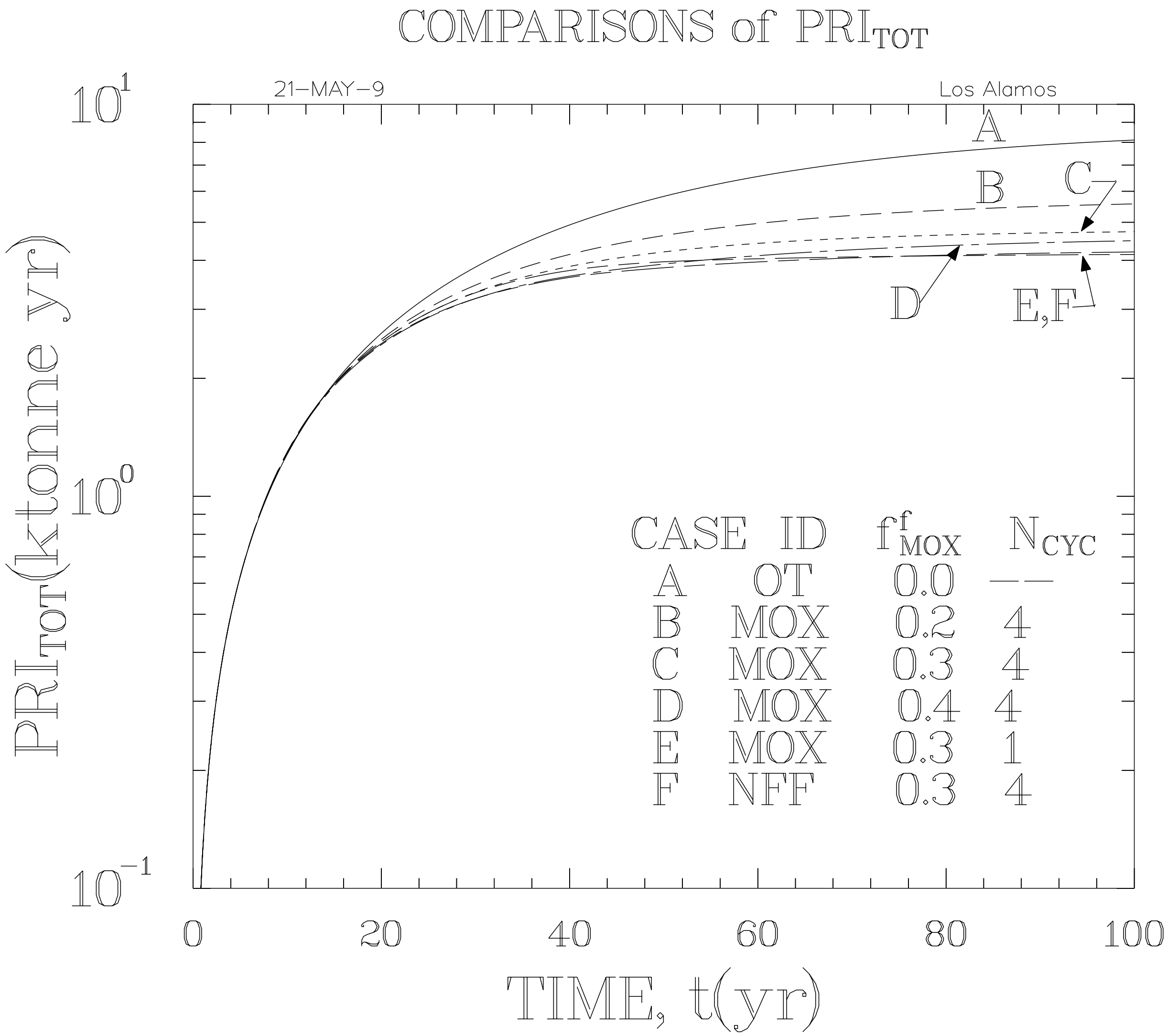


Figure 26. Time dependence of proliferation risk index for most of the key cases considered by this study, as described on the figure and elaborated in the text.