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LONG-TERM TRADEOFFS BETWEEN NUCLEAR- AND FOSSIL-FUEL BURNING

by

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ABSTRACT

A global energy/economics/environmental (E^3) model has been adapted with a nuclear energy/materials model to understand better "top-level", long-term trade offs between civilian nuclear power, nuclear-weapons proliferation, fossil-fuel burning, and global economic welfare. Using a "business-as-usual" (BAU) point-of-departure case, economic, resource, proliferation-risk implications of plutonium recycle in LWRs, greenhouse-gas-mitigating carbon taxes, and a range of nuclear energy costs (capital and fuel) considerations have been examined. After describing the essential elements of the analysis approach being developed to support the Los Alamos Nuclear Vision Project, preliminary examples of parametric variations about the BAU base-case scenario are presented. The results described herein represent a sampling from more extensive results collected in a separate report. The primary motivation here is: a) to compare the BAU basecase with results from other studies; b) to model on a regionally resolved global basis long-term (to year ~2100) evolution of plutonium accumulation in a variety of forms under a limited range of fuel-cycle scenarios; and c) to illustrate a preliminary connectivity between risks associated with nuclear proliferation and fossil-fuel burning (*e.g.*, greenhouse-gas accumulations).

I. INTRODUCTION

The "tension"[1] between nuclear-weapons (NWs) and nuclear-energy (NE) uses of plutonium has generated a deeply divided and evolving debate over the growing commercial (spent fuel) and military (retired NWs) inventories of this Jeckyll-Hydian material[2]. The debate over the best way of dealing with the plutonium legacy (*e.g.*, a "clear and present danger"[3] *versus* a crucial long-term energy resource) has centered primarily on reprocessing of spent nuclear fuel. Over the years, rationale for reprocessing and plutonium recycle has moved[4] from primarily economic and energy-security arenas (up to the mid-1970s); to less-strategic justifications based on improved management of NEs radioactive wastes (up to the mid-1980s); 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 accelerated increases in proliferation potential as inventories of civilian plutonium grow (*e.g.*, each tonne of plutonium in any form is equated to ~100-200 NWs), with the evolution of this situation being driven by processes that are claimed not to be economic for decades to come, if ever. Contemporary arguments supportive of plutonium recycle have focused[5] primarily on non-economic issues that generally invoke environmental (*i.e.*, reduced bio-toxicity of disposed wastes); resource (*i.e.*, uranium conservation through recycle of both uranium and plutonium in LWRs); strategic (*i.e.*, energy independence and option flexibility, particularly for nations without large resource endowments); political (*i.e.*, proliferation risks are claimed to be reduced by reprocessing scenarios that minimize accessible inventories of separated plutonium); and risk-minimizing (technology footing of reprocessing is firmer than direct disposal) rationale.

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) characterization of the proliferation risk; b) regionalization of growths in population and associated energy demand; c) globalization of energy supply and environmental impacts; and d) the relationships between security of energy supply, economic well being, and regional propensities for nuclear proliferation. A central issue in this debate is the degree to which mankind should and can restrict the exploitation of a major sustainable energy source in the pursuit of a world with an acceptably low NW proliferation risk and optimum equity in energy utilization and human welfare (*e.g.*, prosperity with security).

The Nuclear Vision Project[6] at Los Alamos is examining alternative global energy futures over the next $\gtrsim$ 50 years. These futures are being probed within the contextual realities of: a) significantly increased population and energy demand in east Asia; b) the implications this increased population coupled to increased *per-capita* energy consumption has on global energy security; c) the role NE potentially can play in this projected growth, particularly in relieving resource and environmental strain related to the use of nonrenewable fossil fuels; and d) the implications of this growth on the "MW *versus* Mtonne" issue elaborated in Ref. 2. The charting of possible roadmaps leading to desirable future endstates requires at least five essential elements that are incorporated into the Los Alamos study: a) nuclear weapons; b) nonproliferation; c) nuclear materials (NM, *i.e.*, readily fissionable isotopes of uranium and plutonium) inventories; d) energy and environment as driven by economic considerations (E^3); and e) institutional and public acceptance of large technical systems that portend large risk and require unusually high levels of reliability[7] in related operations. Additionally, an overarching determinant of future global endstates is the relationship between global security and energy security, and the way in which that relationship is impacted by the underlying subrelationships between nuclear weapons, nuclear materials, and nuclear energy. Important linkages exist between the NW/NM/NE elements of the Nuclear Visions Project and human activities and consequences related to the pursuit and use of other (both fossil and nonfossil) energy sources that are essential in the search for increased equity in human welfare (again, prosperity with security). In approaching these complex and interconnected issues, the Los Alamos Nuclear Visions Project is comprised of three main components: Workshops and Outreach Activities that are supported by Analyses; this report summarizes the (evolving) Analysis component.

II. APPROACH

The IEA/ORAU Long-term Global Energy Economics Model[8], because of its scope, transparency, and generally broad use[9-13], was adopted as a computational platform for the Nuclear Visions Project. Other E^3 models, however, have and are being considered[14-19]. An operational description of the ERB (Edmonds, Reilly, Barns) model, as it is being modified and applied to the Los Alamos study, is given in Ref. 20. The nuclear economics and fuel-cycle model being evaluated "under" the ERB model is also described in Ref. 20, with Ref. 21. describing the recent evolution of the proliferation-risk model being evaluate in conjunction with global NM flows and NE economics (and related market shares). The NE model being developed for use with the ERB model is based primarily on NM flows within the civilian nuclear fuel cycle. A more detailed description of the analytic approach and related interim results are given in Ref. 22, from which most of the material contained herein derives.

A. Global E^3 Modeling

1. Overview

The desire and need to look forward into the world energy future combines with an inability to predict the future to prescribe a very narrow intellectual tightrope along which any modeler of long-term energy futures must tread.[10] Figure 1 depicts a model as a structure on which the interactions between a range of human activities are examined. Assumptions about relevant human activities provide input to the model, and output is generated in the form of (in the present context) GHG emissions/accumulations, NM inventories, related proliferation risks, economic/energy intensity and development, *etc.* The fact that alternative human activities can lead to large consequential differences contributes to the large uncertainties in "forecasting" future courses of events. As is indicated on Fig. 1, an understanding or appreciation of these uncertainties is developed by the modeling process through various levels of analyses, that includes error [both of omission and (model) distortion or imperfection] analyses. Once consequences (*e.g.*, of GHG accumulations, form and magnitudes of NM inventories, economic impacts of use or restrictions of specific technologies, resource depletion and/or inequities and related security implications, *etc.*) emerge from the global E^3 analyses, recommendations are formulated and placed in a que of many impacts vying to inform decision makers and the creation of regional and global policy. The explication and understanding of the large uncertainties that link possible causes and effects identified by the process described in Fig. 1 are often poorly resolved. In spite of these uncertainties, scenario building using structured models offer a number of attractions that include[10] an ability to:

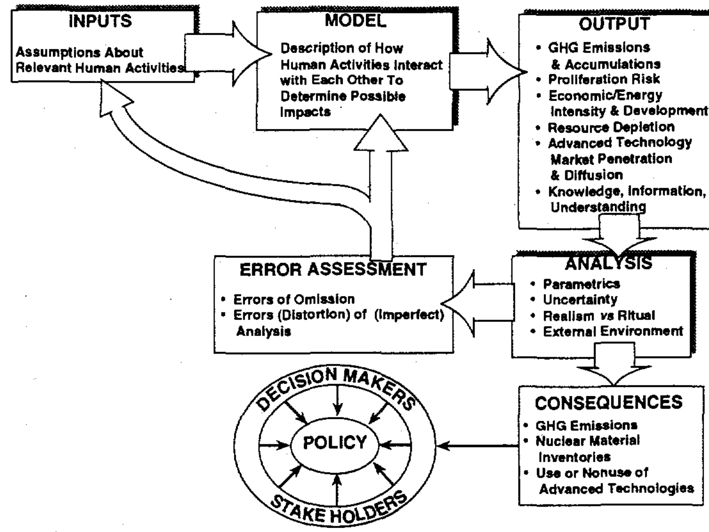


Figure 1. Fundamental components and functionalities of a generic E^3 (energy/economics/environment) model.

- test sensitivities of a given "forecast" to input assumptions;
- explore behaviors under extreme or unlikely conditions;
- assess relative importance of alternative assumptions;
- represent explicitly specific tradeoffs [*e.g.*, GHG *versus* proliferation risk *versus* technology and economic risks associated with the pursuit of advanced (renewable, sustainable) energy technologies];
- understand or explicate uncertain or unresolved linkages (*e.g.*, human activity → GHG emissions; GHG emissions → GHG concentrations; GHG concentrations → temperature change; temperature change → geophysical impacts; geophysical impacts → effects on the welfare of humans and others - similar chains or linkages could be generated for the accumulation of nuclear materials, related proliferation risks, and the time scales required for human commitment).

A wide range of approaches to global energy modeling to provide behavioral forecasting tools have been reported over the last 2-3 decades. Three generic modeling approaches can be identified[10]. First, single-pass analyses establish intuitive relationships between drivers that influence global energy production and use; mismatches between energy production and use in these generally analytic models are resolved by judgment or the assumption that "backstop" energy technologies[23] (*e.g.*, very large resources become available only at high prices) are available to fill the gap. A second generic approach is embodied in the computer-based Linear Programming (LP) models[14,17,23,24] that, upon entry of large amounts of input information, generates either optimized (*e.g.*, GNP) or constrained (*e.g.*, GHG-limited) forecasts. A hybrid between LP, input-output, and energy-accounting models represents a third class of global E^3 models[14,19]; this approach is generally complex and not easily used. The ERB model[8] adopted for the Los Alamos Nuclear Visions Project is base on a behavioral market equilibrium that internally balances energy production and usage; while simplified in comparison to the LP-based or hybrid models, the ERB model was judged to be targeted adequately to the (early) needs of the Nuclear Visions Project, is available to the public, is adaptable to modification, and is generally transparent and well documented.[8,10]

2. ERB Model

The ERB model was developed nearly 25 years ago at the IEA/ORAU under contract to the DOE for the CO_2 Research Division and has been adapted to examine CO_2 emissions by several institutions, including EPA, MIT, EPRI, and GRI. Although an earlier version is available electronically through IEA/ORAU, PNL[25] supports more recent versions. The ERB model is comprised of four main parts: supply, demand, energy balance and GHG emissions (a postprocessor). Supply and demand are determined for six primary energy categories: oil (conventional and nonconventional); gas (conventional and nonconventional); solids (coal and biomass); resource-constrained renewables (hydroelectric and geothermal); nuclear (fission, with fusion being included as a form of solar energy[26]); and solar (excluding biomass, includes solar electric, wind, tidal, ocean thermal, fusion, and advanced renewables; solar thermal is included under conservation). The energy-balance module assures that supply equals demand in each of nine global regions, with primarily electrical energy assumed not to be traded (*e.g.*, assumed to be generated and used within a given global region). The nine global regions are modeled over a ~100-yr time horizon, with the NE and NW status of the regions being tracked by the NE/NM model that has been added to the ERB model. While the GHG emissions are computed after global economic equilibrium and energy balance is achieved for each to the nine 15-year time steps, the nuclear component, as modified for use by the Nuclear Visions Project[20,22], must be evaluated integrally with the iterative approach to economic and energy equilibrium that forms the heart of the ERB model.

A qualitative description of each of the main ERB modules [demand, supply, energy balance, GHG emissions, and nuclear (costing, nuclear material flows, proliferation risk] is given in Ref. 22, Ref. 8 gives a detailed description, and Refs. 20 and 21 give an operational description of the modified model, as used in the Nuclear Visions Project application. Figure 2 gives a simplified graphical description of the computational algorithm used the ERB model and includes the modifications made to support the Nuclear Visions Project; this diagram is a specific extension of that given in Ref. 8.

B. Nuclear Energy Model

The nuclear model developed and implemented for operation "under" the ERB global E^3 model performs primarily three functions: a) determines a "top-level" cost estimate in terms of a cost of electricity (COE, mill/kWeh or $/GJ) that is reformed into the Leontief coefficients[27] used to determine costs and market shares, as described above; b) tracks the flow of key elements throughout the nuclear fuel cycle [*e.g.*, natural uranium (NU), low-enriched uranium (LEU), plutonium (PU), and spent fuel (SF)] for use in subsequent waste and proliferation-risk assessments; and c) performs a multi-attribute utility (MAU) analysis to estimate proliferation risk from the civilian fuel cycle. The costing and material-stream flows are described in Ref. 20, whereas the MAU-based proliferation-risk assessment methodology is elaborated in Ref. 21.

Before costs, NM flows/inventories, and proliferation risk can be estimated, however, characteristics of the fuel cycle must be specified. The nuclear model reported in Ref. 20 is based only on the U/Pu cycle, as implemented in each global region at each time interval by an economically determined ratio of LWR and LMR systems. The LWR in a given global region operates along an exogenously determined MOX recycle trajectory that exponentially transcends from an initial MOX core fraction to a final MOX core fraction with a specified time constant. The LMR system, if economics and technology diffusion time constraints allow, is introduced with a preassigned breeding ratio. Efforts to manage plutonium inventories through regional and temporal control of MOX recycle fraction and (LMR) breeding ratio to date have not been extensive. Generally, plutonium is assumed to flow freely between global regions, where deficits in some regions are corrected by flows from regions with excess plutonium, as long as the global plutonium inventories remains small but positive. Detailed plutonium balance and control remains for future work and higher-fidelity nuclear and costing models. Specifically, implementation of interregional NM flow constraints, breeding

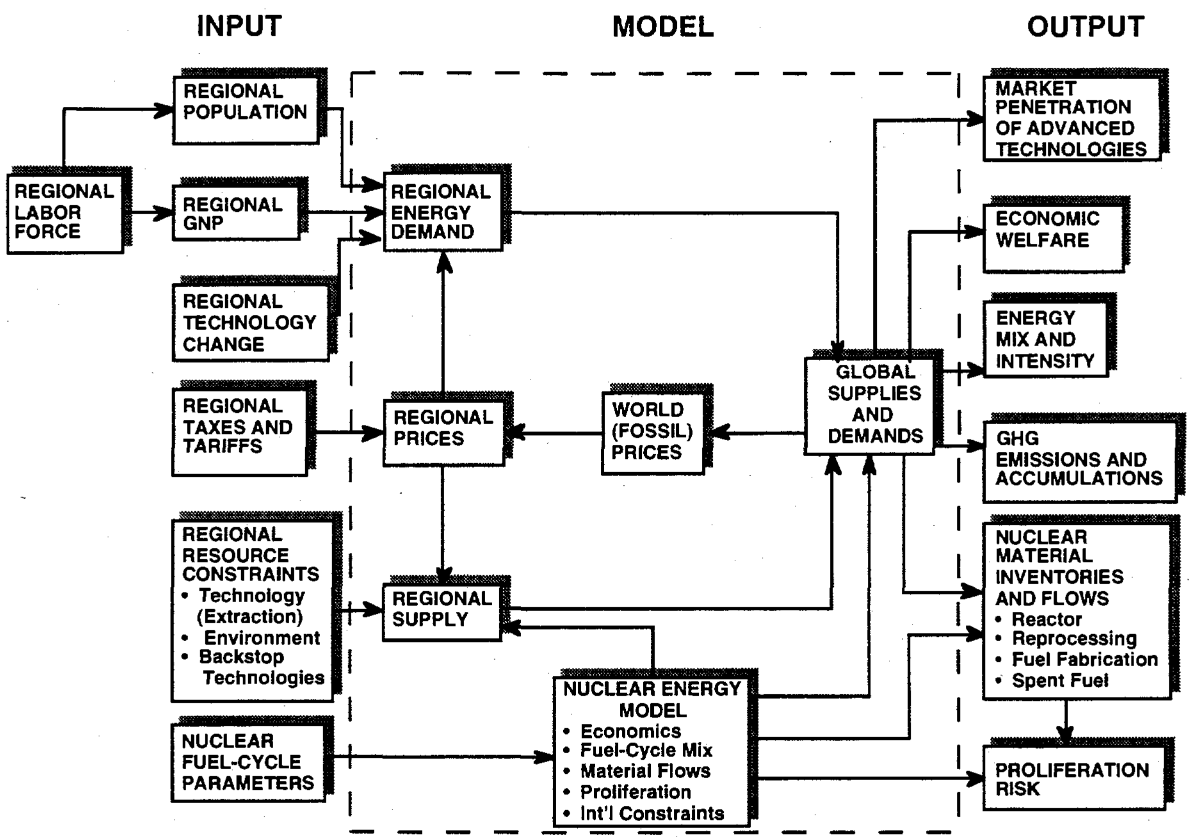


Figure 2. Structure of ERB global E^3 model[8] as adapted for use in the Los Alamos Nuclear Visions Project; four components comprise the ERB model: energy demand; energy supply; energy balance; and GHG emissions (a postprocessor action); the relationships between inputs and outputs, as well as addition of higher-fidelity nuclear model[20] and proliferation-risk model[21] are shown.

ratios driven by inventory and NM need requirements, and cost- and/or sanction-based selections of MOX recycle fractions represent important areas of future work.

Figure 3 illustrates a generic fuel cycle that has been constructed from a series of building blocks identified with key fuel-cycle processes. The simplified species-resolved mass balances described in Ref. 28 based on the kind of input-output analysis depicted on the bottom of Fig. 3 are used to model material flows. Unit capital and operating costs are applied to each of the processes depicted in Fig. 3, from which a fuel-cycle charge for the entire system can be estimated. Plutonium flows and accumulations are monitored for each region as a function of time, with reactor plutonium (RPU), separated plutonium in reprocessing (SPU) and fuel fabrication (MOX), and accumulated in spent fuel (APU) the four major categories being tracked. These plutonium inventories are used as part of the time-dependent proliferation-risk assessment associated with each global region, for a specified set of exogenously determined nuclear and ERB parameters.

C. Proliferation-Risk Model

1. Proliferation Issue

While the present study follows past practice[29-35] and focuses quantitative attention almost completely on the NM streams within the civilian nuclear fuel cycle, the broader perspective outlined in Refs. 29 and 36 has been charted on

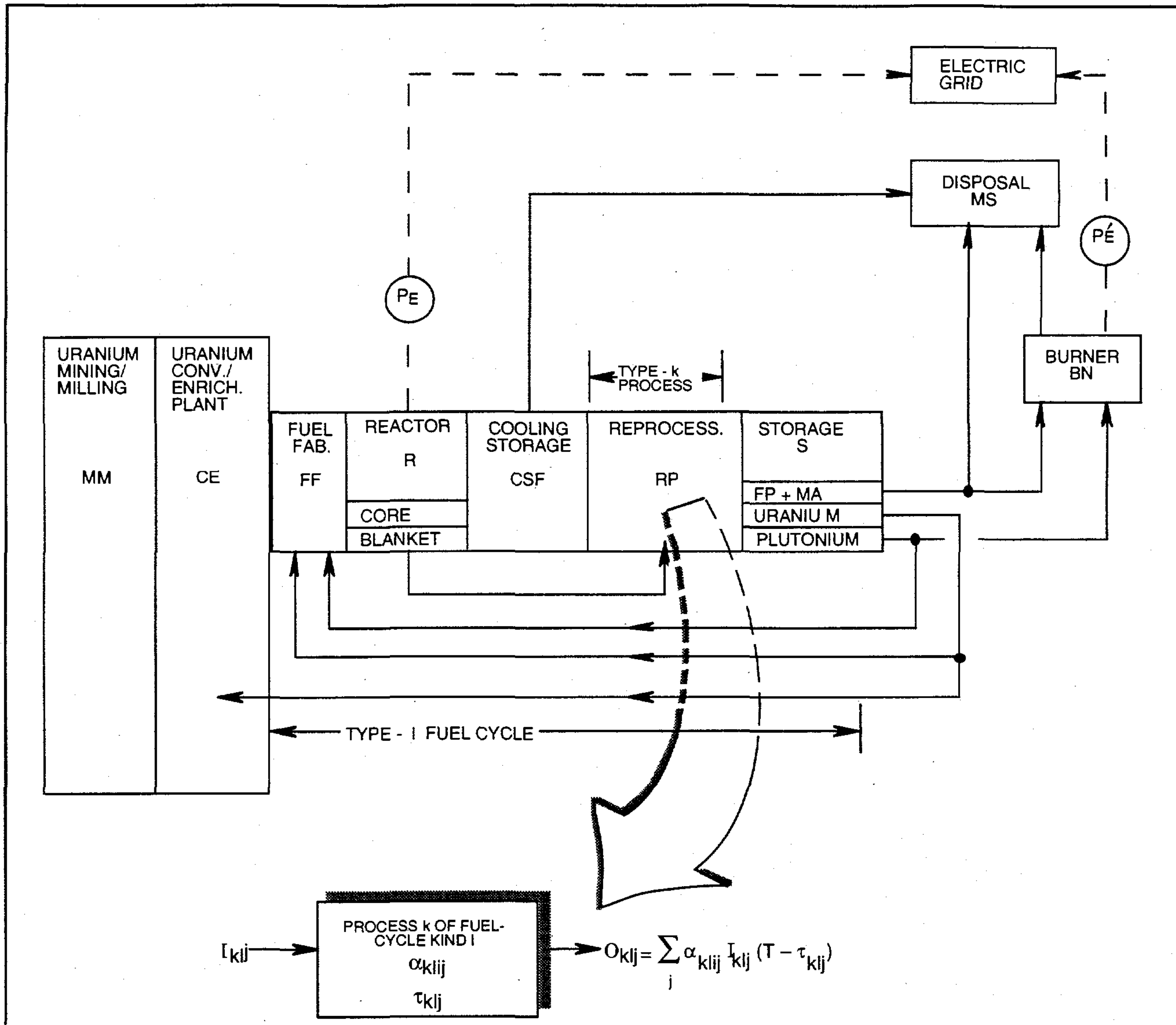


Figure 3. Condensation of the nuclear fuel cycle into a series of generic fuel-cycle building blocks for use in projecting (uranium) resource-constrained, multi-variable optimizations[28] of nuclear-energy mixes and nuclear-material flows. Also shown is a generalized process-flow diagram illustrating formulations used in Refs. 26 and adopted for the fuel-cycle analyses performed in the global E^3 model.

Fig. 4. As discussed in Refs.29 and 36, the decision on the part of a given entity to proliferate and pursue a path towards NW "breakout" can be aggregated into five top-level inputs or drivers:

- INCENTIVES to build, possess, integrate, maintain, and threaten to use nuclear weapons;
- DISINCENTIVES to build, possess, integrate, maintain, and threaten to use nuclear weapons;
- TECHNICAL MEANS needed to build, possess, integrate, maintain, and threaten to use nuclear weapons;
- MATERIAL AVAILABILITY/ACCESS needed to build nuclear weapons;

- LATENCY TRANSFORMATION of previously non-weapons technological and intellectual infrastructure to build, possess, integrate, maintain, and threaten to use nuclear weapons.

Figure 4 illustrates the funneling of these five drivers into the proliferation/breakout decision; eight specific NM safeguard conditions[37] are also indicated. Lastly, once a "go" decision emerges from the "sum" of the five input drivers, the actions listed in the box on the right of Fig. 4 become rate determining insofar as the time at which a "ready threat" actually appears is concerned. The dynamics of this post-decision logic is illustrated on the second frame of Fig. 4. The primary purpose of Fig. 4 is to suggest a methodological framework with which to assess proliferation risk at a level that goes beyond previous approaches centered on NM availability and access. Many of the inputs listed on Fig. 4 that flow into the Incentives, Disincentives, and Latency Transformation decision elements are determined by economic, human-welfare, social/political, environmental, and energy-security issues, that in turn can provide either a negative or a positive feedback to the Materials Availability/Access driver in the proliferation decision. Use of a global E^3 model in the Los Alamos Nuclear Vision project is a first step toward recognizing and quantifying these elements in the NE/NW equation.

2. Proliferation-Risk Model

Two independent applications of MAU theory to the assessment of proliferation risk from the civilian fuel cycle have been reported. References 38,39 examined the value or utility to a potential proliferator of obtaining nuclear-explosive materials from specific points within the nuclear fuel cycle depicted in Fig. 3. While treating the nuclear fuel cycle in more aggregated form, the MAU-based studies reported in Refs. 40,41 treat both the political environment (ENV) and nuclear-weapons aspiration (NWA) level that set the stage for a national decision on proliferation, as well as treating in more detail the method by which specific proliferation criteria or attributes are described and evaluated. The MAU methodology that results from joining the Refs. 38 and 39 and Refs. 40 and 41 approaches, as applied to the above-described nuclear model, is elaborated in Ref. 21.

The essential elements of the combined proliferation-risk model are given in Fig. 5 and the appended footnotes.[21] The ENV and NWA parameters are specified for each global region as a function of time. The ENV and NWA parameters are used, along with attribute or criteria basis (normalization) parameters, to establish the shape of utility and subutility functions posited to describe each of five (proliferator-oriented) criteria[40]: development Time (DT); Warning Period (WP); Inherent Technical Difficulty associated with Material Processing (ITD_{MP}); Inherent Technical Difficulty associated with NW fabrication (ITD_{NW}); and Cost (CST). Referring to Fig. 5, once ENV, NWA, and the state of sanctions (SANC) are specified for a given global region and time, and using the MOX/LWR and LWR/LMR mixes as a proxy for the fuel cycle FC_k, the $j = 5$ attributes are applied to each of $i = 4$ (HEU, SPU, MOX, and SFT) material streams. Plutonium undergoing fissioning in a reactor, RPU, is not included at this point in the proliferation-risk assessment, under the assumption the reactor plutonium that is actively undergoing fission is "safe and secure". Reference 21 summarizes details for each of the j criteria or attributes and each of the i material streams that comprise the core of the proliferation-risk model.

Using weights generated from pairwise comparison techniques[32,42], weighted utilities for each material stream are generated as a function of time for each global region. These material-stream utilities are then time-discounted and summed to give a Proliferation-Risk Index[28,39], PRI_{ilm}, for stream i, region l, and time m. This PRI value represents a geometrically weighted average of the particular LWR/LMR mix, as determined by the cost-minimized, market-penetration-rate-constrained value of the ratio LWR/LMR. Generally, the material stream with the maximum PRI is selected as the index to be monitored, $PRI_{lm} = MAX\{PRI_{ilm}\}$. Lastly, use once again of pairwise comparison techniques[42] to weigh the importance of region l compared to a reference region l′ in terms of importance of the respective value PRI_{lm} gives weights needed to generate a time-evolving global proliferation-risk index, PRI_m, relative to a reference region (*e.g.*, the US).

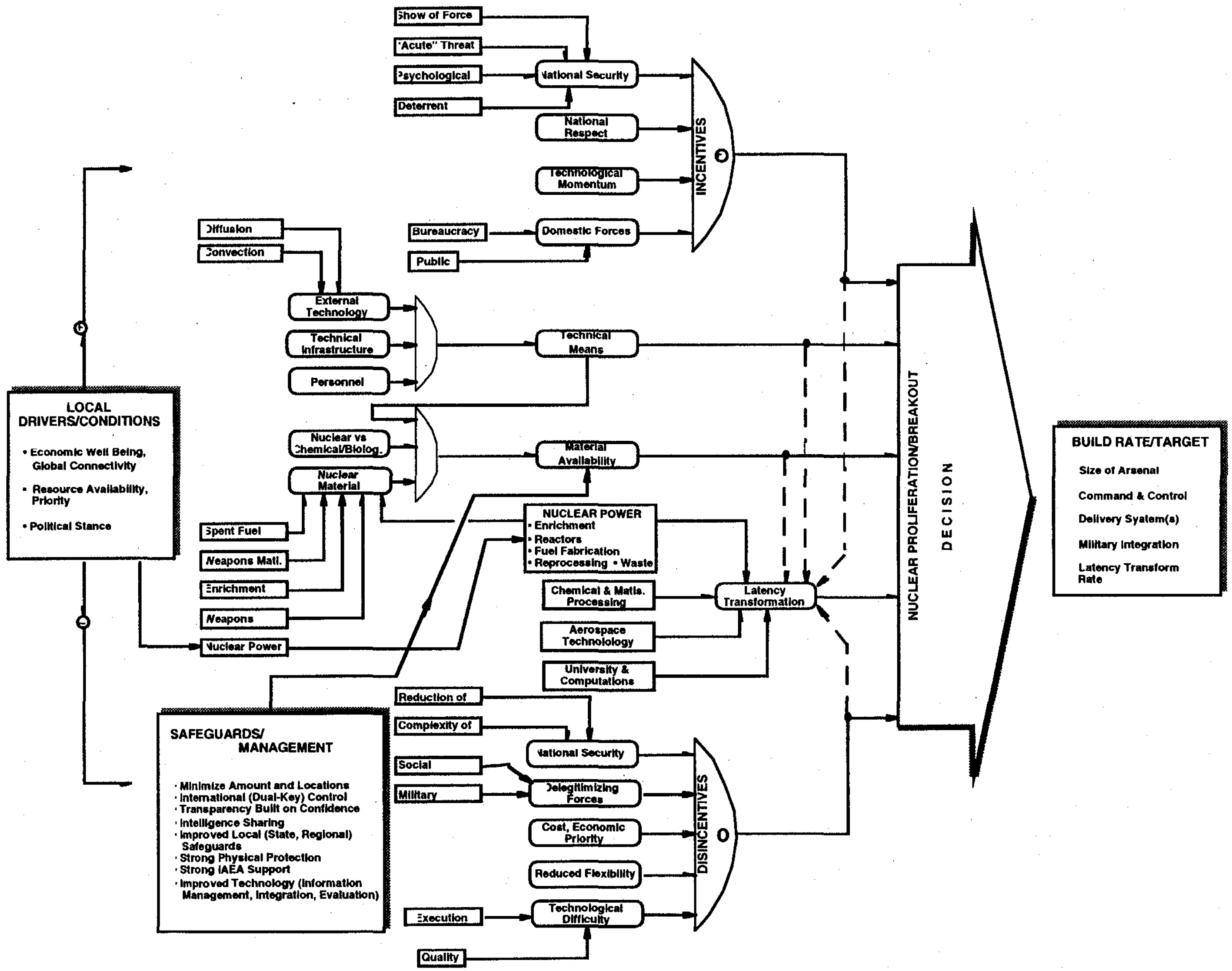


Figure 4A. Systems framework suggested for assessing proliferation risk. A: Overview.

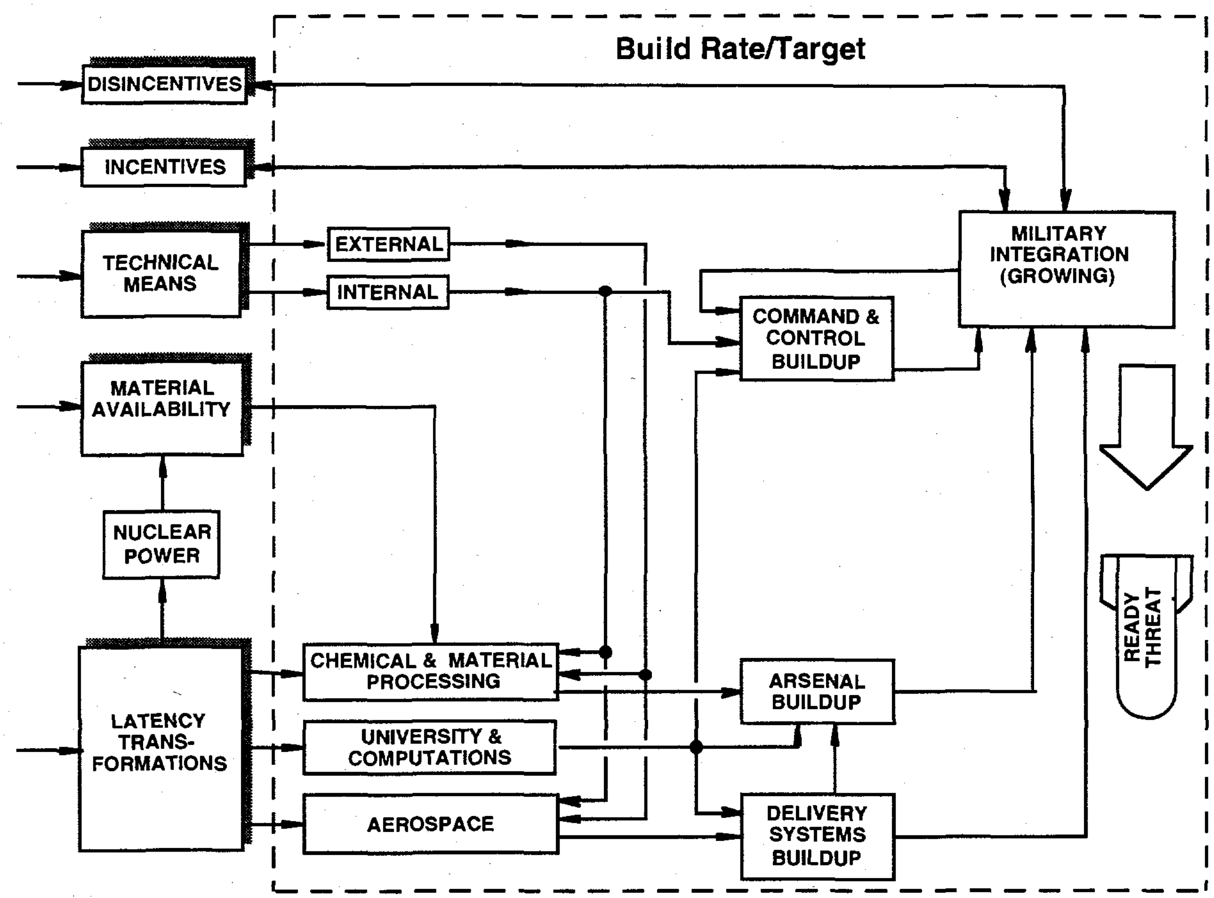


Figure 4B. Elaboration of "build rate/target" box indicated on part A.

III. RESULTS

A. Overview

A sampling of the typical results from the modified ERB model given in Ref. 22 are reported herein. Table I summarizes an ensemble of six cases that is centered on "business-as-usual" (BAU) conditions (Case A) and have been selected primarily for illustrative purposes. Except for the modifications described in Sec. II.A., the BAU Case-A parameters are those in the "as-received" version of the ERB model[12,25]. Table II lists key parameters used in the nuclear model that runs "under" the ERB model. Most of these parameters remained fixed for the BAU and the five perturbation cases described in Table II, and differ somewhat from those reported in Ref. 20. None of the extensive parameter input required to evaluate the proliferation-risk model are given here[21]. While both the nuclear fuel-cycle/material-flow and proliferation risk models have been developed to express broad regional and temporal variations, most of the illustrative results reported here model a world that, aside from energy-demand-driven NM inventories, is relatively uniform from the viewpoint of proliferation risk (*e.g.*, parameters listed on Fig. 5).

The essential elements differentiating the six cases described in Table I are: a) the degree of plutonium recycle (to LWRs); b) the cost of nuclear power; c) the LWR/LMR mix (controlled by relative costs); and d) the imposition of a fossil-fuel carbon tax. Control of the NE market share through costs (*e.g.*, either NE capital cost or tax-enhanced fossil-fuel prices) is a motivating factor for these parametric choices. The BAU (base) Case A is characterized by no

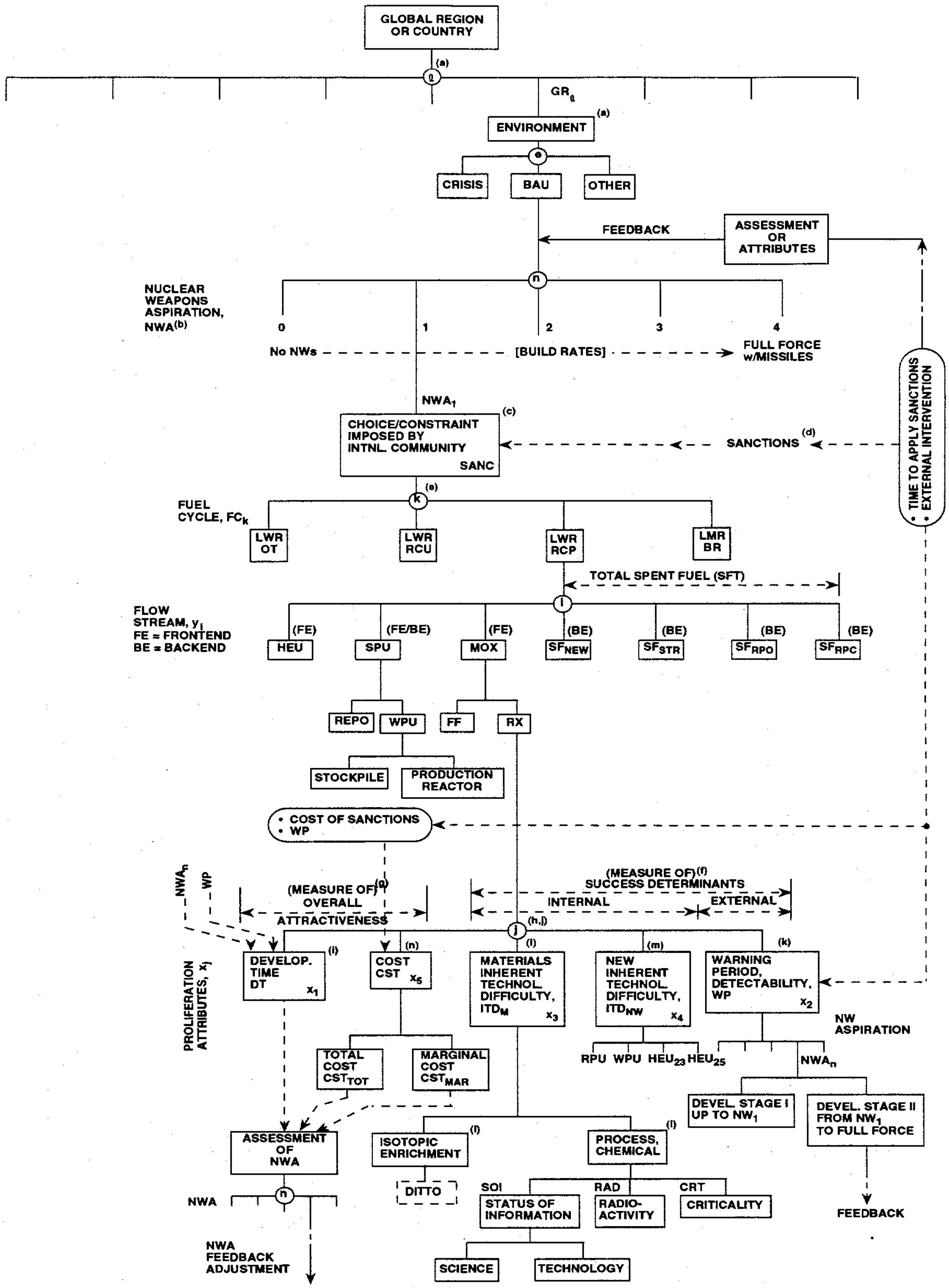


Figure 5. Logical sequence diagram depicting algorithm for assessing proliferation risk as determined by combining the MAU-based approaches reported in Refs. 38, 39, and Refs. 40, 41; refer to the Nomenclature for definition of symbols/acronyms.

Footnotes for elaboration of Fig. 5 taken largely from Ref. 40.

(a) The choice of country/region (l) sets characteristics, preferences priorities, *etc.* through which the political environment (ENV) and level of nuclear-weapons aspiration (NVA) are determined; both ENV and NWA for a given l may change with time, as well as with similar conditions existing in other countries/regions.

(b) The levels of NWA = (0,4) corresponds in rank order to: a) no NWs (0); one crude non-deliverable device (1); c) 10 deliverable NWs per year (2); d) 100 deliverable NWs per year (3); and e) >1000 deliverable NWs per year (4); depending on the rank order, a value is assigned to NWA_{lm} that is used to modify the risk-aversion factors (RAF_i or RAF_j) for that region at that time.

(c) The choices/constraints imposed through sanctions ($SANC_{lm}$) by the international community can impact: a) the kind of fuel cycle available or allowed; b) the kind of facilities allowed within the country/region; and c) various international agreements on the use of facilities and sanctions related to illegal use.

(d) Sanctions $SANC_{lm}$: political pressure; curtailment/cancellation of credits, technology exchanges, agreements of cooperation, particularly with respect to nuclear assistance; variations between "light" sanctions to "heavy" sanctions (including preemptive strikes).

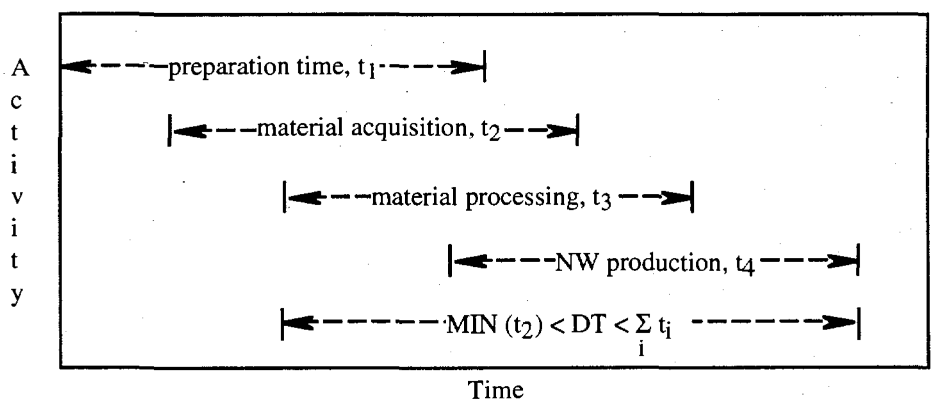
(e) The parameter k defines an alternative system which, for a given country/region, includes technological characteristics, institutional constraints, and sanctions to be imposed in case of violation and discovery thereof; in the context of the present study, the parameter k is used to differentiate between LWRs and LMRs and any conditions applied temporally or regionally to exclude or constrain technologies associated with either or both.

(f) Attributes j = 2, 3, and 4 (*e.g.*, WP, ITD_{MP}, and ITD_{NW}) contain all the elements that affect the probability that the (proliferation) effort will be successful for a given set (ENV_{lm}, NWA_{lm}, FC_k, and y_i); these attributes are further divided into "external" and "internal" (to the proliferation effort) classes.

(g) Attributes j = 1 and 5 (DT and CST) contain all the elements that make one pathway more desirable than another, given the successful completion of the effort[(f)]

(h) The following criteria are used in selecting these j = 5 attributes: complete; operational; non-redundant; and minimum size (*e.g.*, number and complexity).

(i) The following diagram depicts the four primary time lines that determine the NW Development Time, DT:



Costs (CST, x_5) and probabilities for detection or Warning Period (WP, x_2) can be associated with phases of NW development. A simpler (single phase) approach is taken in the present model for parametrically assessing proliferation risk in the context of the ERB global E^3 model[8,20].

(j) The proliferation pathway/process/procedure is divided into two phases and two modes:
Phases:
- preparation/prediversion: R&D, facilities design and construction, but no diversion of material from the commercial operations;
- diversion: nuclear fuels, materials being diverted.

Modes:
- covert: slower progress (higher DT), reduced probability of detection (reduced WP);
- overt: faster progress (reduced DT), greater activity and higher probability of detection (increased WP)

The combination of Phases and Modes gives 4 "top-level" pathways.

(k) The Warning Period, WP, is measured in terms of the fraction of the NW development/production task[i] remaining to be completed at the time of detection. As discussed in Ref. 21, this fraction, $(1 - t_D/DT)$, where t_D is the time of detection, can be expressed in terms of a growing probability of detection (*e.g.*, a "failure" rate in the parlance of reliability theory) and a NW production function, P(t), giving the fraction of the NW development/production activity remaining at time t. Important tradeoffs exist with most of the other (assumed independent) attributes used to assess the over all proliferation risk.

(l) The inherent technical difficulty associated with material processing, ITD_{MP}, is divided into isotopic-enrichment and chemical processing operations, each being interpreted in terms information availability (both technological and scientific), radiation hazard, and criticality hazard; all evaluations must be based on the (evolving) scientific, technological, and industrial capability and infrastructure of a given country/region.

(m) The inherent technical difficulty for actual fabrication of the NW, ITD_{NW}, is also dependent on the (evolving) scientific, technological, and industrial capability and infrastructure of a given country/region; this attribute, however, is measured only in terms of the isotopic composition of the nuclear explosive being assembled, which for plutonium is measured in terms of integrated fuel burnup, BU(GWtd/tonne); HEU is given the highest utility[40], although clandestine uranium enrichment in competition with sources from the civilian fuel cycle is not included in the results reported herein.

(n) The cost attribute, CST, is divided into total cost, CST_{TOT}, and marginal cost, CST_{MAR}. Total cost is related to proliferation pathways base on a "greenfield" construction endeavor and includes direct capital, O&M, personnel, and capital-service charges that are integrated over relevant periods of time and discounted to the present. Marginal costs include the costs of replacing lost power (if nuclear material is taken from the commercial sector, and donor power-plant availabilities are decreased), as well as the cost of sanctions; the cost of sanctions is strongly coupled to the WP and DT attributes, the NW-development/production technologies selected, and the probabilities that sanctions will be enforces at a given level once the proliferation action is detected).

plutonium recycle, no LMRs, and no carbon taxes. Case B examines the impact of increased LWR costs, while disallowing an economically viable LMR option. The impact of increased fossil-fuel charges imposed by a (naively) simple carbon tax is investigated in Case C; this carbon tax will ultimately serve as a proxy against which the costs of sustainable technologies (*e.g.*, like NE or biomass) that reduce global GHG emissions by a given amount must be compared on an integrated, present-value basis[12]. Introduction of LMRs (of reduced cost compared to the BAU base case) is considered in Case D. Both Cases E and F examine the impact of plutonium recycle to LWRs without carbon taxes imposed on the use of fossil fuels and without the introduction of LMRs; these two plutonium recycle cases differ in whether or not a regional dependence is implemented on the rate of and level at which is plutonium recycled.

The results described in the following section represent a sampling from more extensive results collected in Ref. 22. The primary motivation here is: a) to describe the BAU case in comparison with results derived from other studies; b) to model the accumulation of plutonium under a limited range of fuel-cycle scenarios; and c) to illustrate a preliminary connectivity between risks associated with nuclear proliferation and GHG accumulations.

Table I. Summary of Case Characteristics/Parameters

Case	LWR Plutonium Recycle	LWR Unit Cost UTC_{LWR} (\$/We)	Relative LMR Cost UTC_{LMR}/UTC_{LWR}	Carbon Tax
A	No	Nominal[(a)]	High[(b)]	No
B	No	High[(c)]	High	No
C	No	Nominal	High	High[(d)]
D	No	Nominal	Nominal[(e)]	High
E	Yes[(f)]	Nominal	High	No
F	Yes[(g)]	Nominal	High	No

(a) $UTC_{LWR} = 2.0$ \$/We

(b) $UTC_{LMR} = 2.0 \times UTC_{LWR}$

(c) 4.0 \$/We

(d) 40 \$/tonneC/15yr, starting in 2005

(e) $UTC_{LMR} = 1.3 \times UTC_{LWR}$

(f) all regions achieve 15% MOX in a 40-yr exponentiation time; some regions experience a plutonium deficit before ~2100, but global plutonium in spent fuel remains positive.

(g) region-dependent final MOX fraction and exponentiation time; all regions do not sustain a plutonium deficit before ~2100.

Table II. Summary of Key Input (Fixed or Computed) to Nuclear Fuel-Cycle Model

INITIAL PARAMETERS[(a)]	
Accumulated uranium mined by 1990, $U_0(kg)/10^8$	2.00
Installed nuclear capacity as of 1990, $P_{E0}(MWe)/10^5$	3.40
Accumulated spent fuel as of 1990, $M_{SF0}(kg)/10^7$	5.89
Accumulated MOX fuel as of 1990, $M_{MOX}(kg)/10^6$	3.00
Initial plutonium in reactors, $M_{PU0}(kg)/10^5$	2.56
LWR REACTOR PARAMETERS	
Fuel burnup, BU(MWd/kgHM)	40.0
Fuel replacement or life time, τ_R(yr)	3.0
Specific inventory, SI(kg/MWt)	26.7
Fraction of all actinides that are minor, f_{MA}	0.0
Fraction of all plutonium that is fissionable, f_{Puf}	0.60
Thermal-to-electric conversion, η_{TH}	0.325
Plant availability, p_f	0.70
Fraction of fissions from ^{235}U, f_{25}	0.40
Engineering gain, Q_E[(b)]	25.

Table II. Summary of Key Input (Fixed or Computed) to Nuclear Fuel-Cycle Model (Cont-1)

ENRICHMENT AND (LWR) REACTOR CONCENTRATIONS	
Plutonium concentration in spent fuel, f_{Pu}	0.0090
Effective breeding ratio for OT→MOX, BR_o	0.3018
Weight fraction ^{235}U in ER product stream, x_p	0.0300
Weight fraction ^{235}U in ER feed stream, x_f	0.0071
Weight fraction ^{235}U in ER tails stream, x_t	0.0020
Weight fraction plutonium in MOX, x_{Pu}	0.0400
Weight fraction ^{235}U in RU stream, x_d	0.0121
Total burnup fraction for LWR, x_{BU}	0.0298
^{235}U burnup fraction, x_{BU25}	0.0179
Uranium ore grade (weight fraction), $x_{ORE}/10^{-6}$	5.00
LMR PARAMETERS	
Thermal-conversion efficiency for LMR, η_{TH}	0.40
Plant availability, p_f	0.70
Burnup for LMR, BU(MWd/kg)	80.0
Breeding ratio for LMR, BR	1.00
Fuel concentration in LMR, x_{Pu}	0.1000
Specific inventory for LMR, SI(kg/MWt)	67.6
Total burnup fraction for LMR, x_{BU}	0.0596
Simple doubling time for LMR, DT(yr)	∞
Engineering gain, Q_E	25.
Market penetration time constant, λ_c(1/yr)	0.169
RECYCLE PARAMETERS	
Initial fraction of load supplied by MOX, f_{MOXo}	0.0010
Final fraction of load supplied by MOX, f_{MOXf}	varied
Half-time for $f_{MOXo} \rightarrow f_{MOXf}$, T_{MOX}(yr)	varied
Initial separated plutonium inventory, $M_{SPUo}(kg)/10^5$	1.20
Time when $f_{MOXo} \rightarrow f_{MOXf}$ rampup starts, t_{MOXo}(yr)	1990
MOX core burnup, BU_{MOX}(MWd/kg)	40.0
Hold-up time for LWR reprocessing, τ_{RP}(yr)	1.0
Hold-up time for LWR fuel fabrication, τ_{FF}(yr)	0.5
Hold-up time for LMR reprocessing, τ_{RP}(yr)	0.3
Hold-up time for LMR fuel fabrication, τ_{FF}(yr)	0.3

Table II. Summary of Key Input (Fixed or Computed) to Nuclear Fuel-Cycle Model (Cont-2)

COSTING PARAMETERS	
Fitting constant for uranium ore cost, U_1	0.00031
Fitting constant for uranium ore cost, ν	0.6300
Unit cost of uranium ore in 1990, UC_{MMo}(\$/kgU)	52.6
Unit cost of uranium conversion, UC_{CV}(\$/kgU)	5.0
Unit cost of uranium separative work, UC_{SW}(\$/kg SW)	100.0
Unit cost of uranium fuel fabrication, UC_{FF}(\$/kgU)	200.0
Unit cost of MOX fuel fabrication, UC_{FF}(\$/kgU)	400.0
Unit cost of spent fuel storage, UC_{SF}(\$/kg/yr)	10.0
Unit cost of fission-product storage, UC_{FP}(\$/kg/yr)	10.0
Unit cost of SF/FP transport, UC_{TR}(\$/kgU)	0.0
Unit cost of reprocessing LWR, UC_{RP}(\$/kgHM)	1000.
Unit cost of reprocessing LMR, UC_{RP}(\$/kgHM)	1500.
Unit total cost for LWR, UTC_{LWR} (\$/We)	1.25 → 2.0[c]
Unit total cost factor, $f_{UTC} = (UTC_{LMR} - UTC_{LWR})/UTC_{LWR}$	1.0
Unit total cost for LMR, UTC_{LMR}(\$/We)	4.0[d]
Fixed charge rate for LWR, FCR_{LWR}(1/yr)	0.09
O&M charges as fraction total capital for LWR, f_{OM}^{LWR} (1/yr)	0.02
Fixed charge rate for LMR, FCR_{LMR}(1/yr)	0.09
O&M charges as fraction total capital for LMR, f_{OM}^{LMR} (1/yr)	0.02
Unit cost(value)[e] of plutonium, UC_{PU}(\$/kgPu)/10^4	1.85
Unit cost(value)[e] of MOX, UC_{MOX}(\$/kgPu)	738.

(a) global values.

(b) ratio of total electric power to power used on site; the net plant efficiency is $\eta_P = \eta_{TH}(1 - 1/Q_E)$.

(c) varied with time.

(d) value selected to assure LMR does not compete with LWR under BAU conditions.

(e) value based on saved enrichment costs, accounting for reprocessing and (increased) fuel-fabrication costs[28].

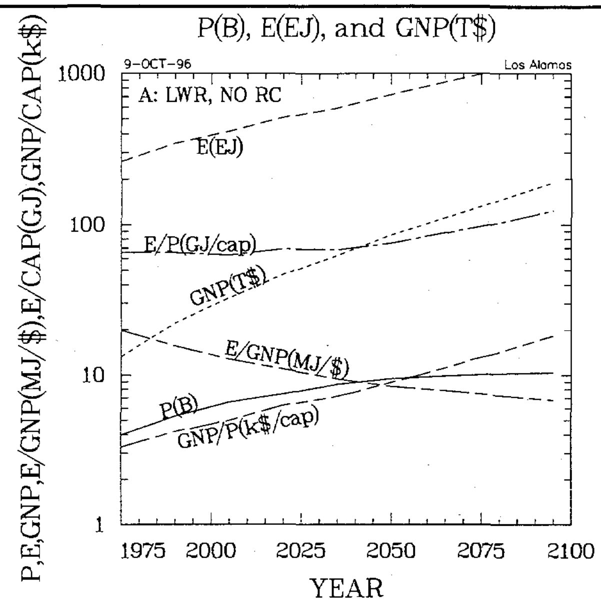


Figure 6. Time evolution of global population, P (an exogenous input); total primary energy demand, E; Gross National Product, GNP (baseline input, modified by energy prices); primary energy per GNP, E/GNP; primary energy per capita, E/P; and GNP *per-capita*, GNP/P; for the BAU Case A (Table I).

B. Sample Results

1. Business-As-Usual (BAU) Base Case

The long-term energy scenario computed by the ERB model is driven by exogenous inputs of (regional) population and (base) GNP growths, along with assumptions about regional technology improvements, labor force, and tax and tariff rates. The base GNP input is modified to reflect the evolution of world fossil-fuel prices needed to clear markets in each of the nine 15-year time steps needed to take the computation out to the year 2095 (starting from 1975). Figure 6 gives the population-growth driver, along key aggregated economic and energy parameters that result for the BAU Case A. The population growth assumed for the BAU Case A stabilizes at ~10.5 billion persons, and price-adjusted GNP growth rate decreases from 2.6 %/yr over the period 1990-2005 to ~1.7-1.8 %/yr in the latter part of the 21^{st} century. The *per-capita* energy consumption is relatively flat out to the year 2030, and increases slightly thereafter. Likewise, the *per-capita* GNP shows a steady increase from the present ~4 k$/yr to 20 k$/yr by the year 2100, whereas the decrease in global energy intensity shows an improvement from $\gtrsim$ 10 MJ/$ to $\lesssim$ 6 MJ/$. Regional and temporal breakdowns of these demographic and economic parameters are provided by the ERB model results[22].

a. Primary Energy Usage

Aggregation of the nine global regions into industrialized and developing sectors (*e.g.*, referring to the Nomenclature, Industrialized Countries = USA + OECD-E + OECD-P + FSU/EEU; Developing Countries = $CHINA^+$ + ME + AFR + LA + SEA) leads to Fig. 7; generally, the cross-over in total (annual) energy demand is ~10-15 years later than suggested from other studies[43]. The breakdown into primary energy categories of this global demand is shown in Fig. 8 for the Case-A conditions. The time dependence of the global mix of the six primary energy sources [*e.g.*, oil, gas, solids (coal + biomass), nuclear, hydroelectric, and solar-electric (solar-thermal energy is described in the ERB model as a conservation measure)] generally reflects a large unit costs used for solar-electric and biomass, which results in the relatively small shares [only ~4.3% of the solid primary energy consumption (labeled in Fig. 8 as "coal") is attributed to biomass in 1990, which grows to 9.0% by 2005, 9.3% by 2095]. Generally, the BAU Case A suggests a growth of 1.2-1.3 %/yr in primary energy usage after the year 2000, compared to 1.9 %/yr (1975-1990), 2.1 %/yr (2035-2050) and 1.8%/yr (2080-2095) for the exogenous global population growth. The growth in world GNP decreases from 3.5 %/yr (1975-1990), to 2.1%/yr (2035-2050), and to 1.8%/yr (2080-2095).

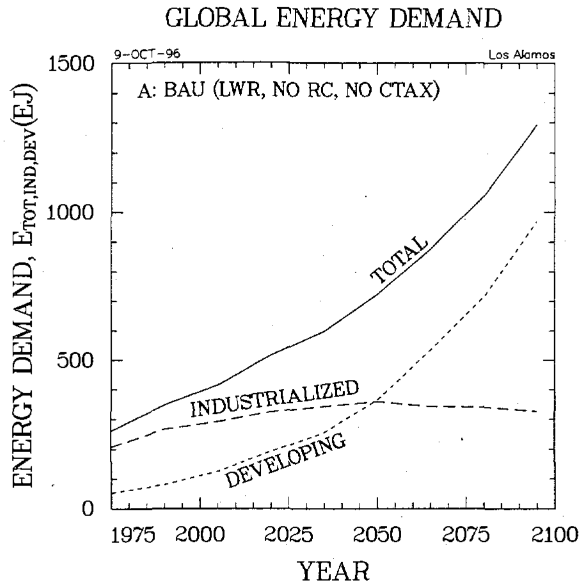


Figure 7. Base case BAU total primary energy demand as a function of time, showing a breakdown into industrialized (USA + OECD-E + OECD-P + FSU/EEU) and developing ($CHINA^+$ + ME + AFR + LA + SEA) global sectors.

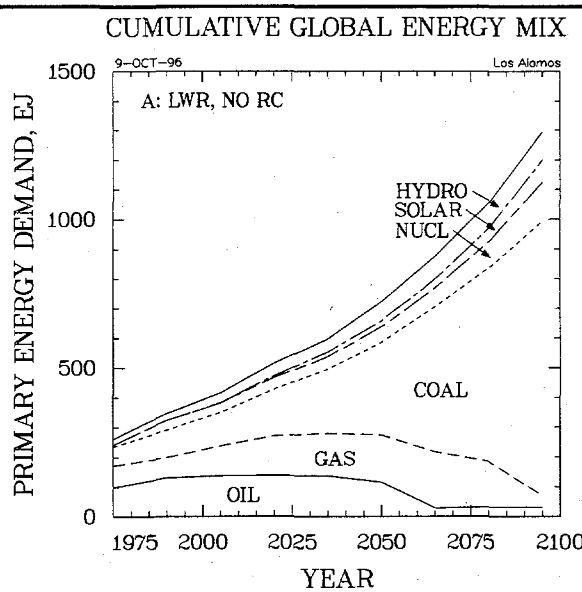


Figure 8. Time dependence of global demands for primary energies for the BAU Case A.

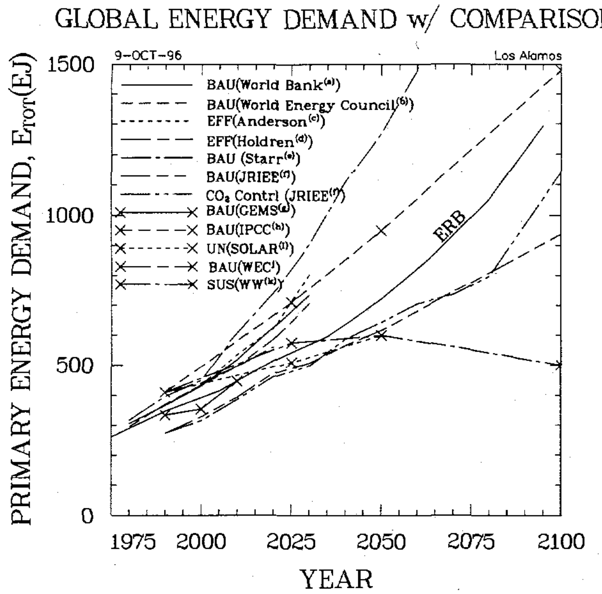


Figure 9. Comparison of BAU (Case A) primary-energy demand scenario generated from the ERB model with other studies:

(a) Refs. 44,45; (b) Ref. 46; (c) Refs. 44,47; (d) Ref. 44; (e) Ref. 48; (f) Ref. 48; (g) Ref. 50; (h) Refs. 51,52; (i) Ref. 52,53,58; (j) Ref. 46,53; (k) Ref. 52.

b. Comparisons

Figure 9 gives a collection of recent prognostications, including BAU, high-efficiency, and/or sustainable scenarios, against which the BAU Case A is compared. While the range of global demand projections is large, with some of this range being created by the inclusion or exclusion of indigenous fuel sources[44], the ERB Case A is in the mid-to-upper range of other projections, while indicating a later cross-over of industrialized- *versus* developing-country demand.

c. Nuclear Energy

The temporal and regional dependence of nuclear energy is shown in Fig. 10, which gives annual nuclear-electric consumption rather than capacity. The nominal annual growth decreases initially from 9.3 %/yr (1975-1990) to negligible values around the year 2000, but then increases to ~1.1-1.4 %/yr in the first half of the 21st century, with subsequent increases of 1.7 %/yr (2050-2065), 2.1 %/yr (2065-2080), and 2.7 %/yr (2080-2095); this growth in global NE usage is driven primarily by increased use in the developing regions of the globe. Figure 10 incorporates recent NE scenarios[54,55], which indicate that the BAU Case-A ERB model is suggesting a somewhat lower NE demand.

The growth in NE depicted in Fig. 10 for the BAU Case A (LWRs, no plutonium recycle, no carbon taxes) is accompanied by a growing global inventory of plutonium that resides primarily in a range of spent-fuel forms and in actively fissioning reactor inventories. The total [accumulated (spent fuel), separated, and reactor] plutonium inventories are shown as a function of time and region in Fig. 11. The proliferation risk, as measured by either the material-stream-maximum utility or the proliferation-risk index [$(PRI_i)_{MAX,l}$, which is the discounted sum of utilities using a 2 %/yr discount rate[39]] for the BAU case is driven primarily by the inventories and related utilities associated with the spent-fuel material stream. Depending on fuel-cycle scenario and NE growth rates, the fuel-cycle stream that is contributing to the PRI evolves/shifts in time[21,22].

d. Proliferation Risk

The regional dependence of PRI is dominate by the developed countries, which have the larger inventories of spent fuel. The parameters used to generate these proliferation-risk metrics are summarized in the Ref.-21 model description, which at the present level of fidelity does not differentiate between "proliferation" and "diversion". Furthermore, the degree to which the risk associated with either depends on the actual inventories in a given material stream remains uncertain, but the threshold inventories used to generate the results reported here[21] are set at relatively high values. Generally, the global proliferation risk must be determined using a weighting of the regional PRIs at a given time. The high inventory-driven PRI for the USA, for instance, from the perspective of the United States would be given a low weighting relative to other global regions having lower PRIs. Using such a weighting

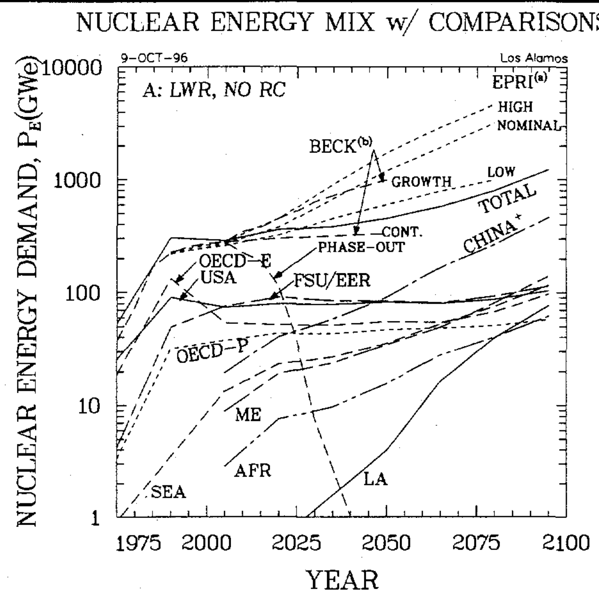


Figure 10. Time and regional dependencies of nuclear energy demand for the BAU Case A (annual energy generation rather than capacity is reported), including recent projections/scenarios.

(a) Ref. 54; (b) Ref. 55.

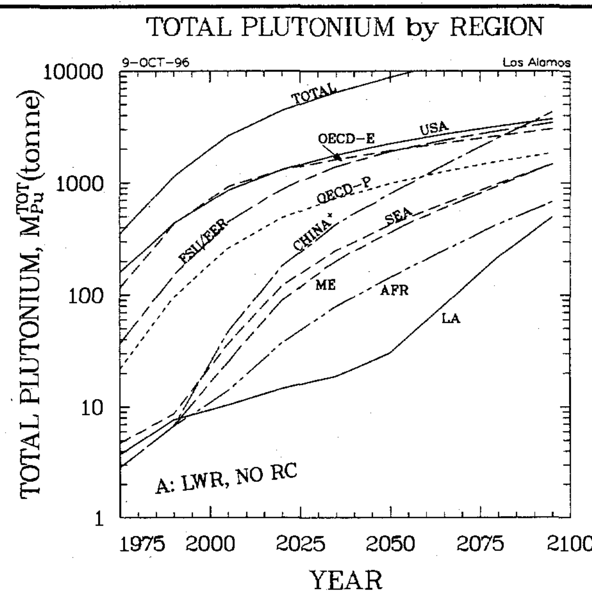


Figure 11. Time and regional dependencies of total plutonium inventories for BAU Case A; since little or no plutonium recycle is allowed for this case, separated plutonium inventories (in processing, in a range of separated forms, and in fuel fabrication as MOX) are negligible (re: Fig. 14).

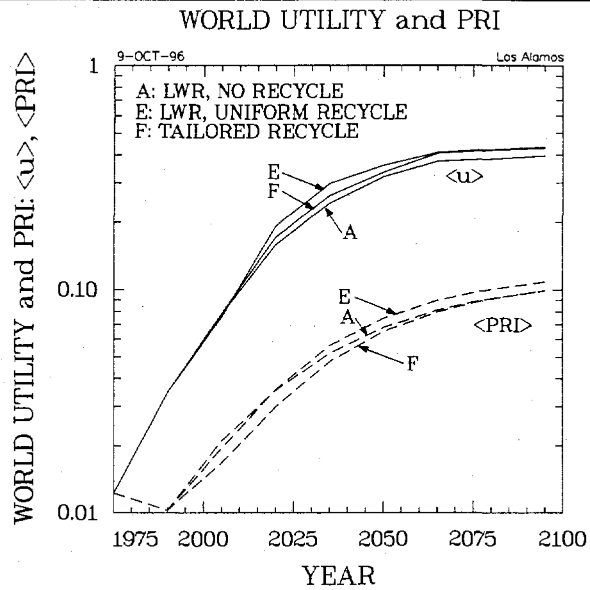


Figure 12. Time dependencies and comparisons of global proliferation-risk utility and index for range of recycle case embodied in Case A (no recycle), E (regionally uniform recycle), and F (regionally tailored recycle).

scheme[21], the time-evolution of the global PRI and associated global utility depicted in Fig. 12 result. The magnitude of global PRI or utility must ultimately be related to a specific (global) consequence, but on a relative basis the global PRI presently serves as a proxy to be correlated with other global risks associated with energy use (*e.g.*, GHG emissions and accumulations) or non-use (*e.g.*, stunted improvements in human welfare, as measured crudely by GNP/capita). As for the PRI metric, the consequence of GHG accumulations or reduced human welfare remain to be quantified in terms of specific and comparable consequences.

e. Carbon Dioxide Emissions

The global and regional emissions of carbon dioxide for the BAU Case A are shown as a function of time in Fig. 13. Similar estimates for N_2O and CH_4 are available from the ERB model. The dominance of China in contributing CO_2 to the atmosphere for the Case-A conditions occurs sometime after the year 2025.[22] The relatively long atmospheric residence time for CO_2 indicates that most of the integrated emissions depicted in Fig. 12 will be retained in the atmosphere on the time scale of this computation; the atmosphere presently contains a total gaseous carbon mass of $M_{CO_2,1990}$ = 740 Gtonne[56]. The ratio of the integrated CO_2 emissions measured from the ERB base year (1975), M_{CO_2}, to $M_{CO_2,1990}$ is used as an index of GHG risk, and is correlated with PRI. While this correlation indicates the expected increase in risks associated with proliferation and GHG emission with growths in population and the welfare of those populations, expression of this relationship into a consequence space through some yet-to-be-determined "Jacobian" transformation is expected to change the form (*e.g.*, slope and curvature) of this relationship. The primary value of the PRI *versus* $M_{CO_2}/M_{CO_2,1990}$ relationship, however, is as an indicator of relative shifts and changes when other scenarios (*e.g.*, Table I) are considered.

2. Plutonium Recycle

For the BAU Case A, little recycle of plutonium is allowed, and the separated plutonium in either reprocessing or in the form for MOX is small. Two cases involving plutonium recycle to LWRs are indicated on Table I: a) Case E uniformly allocates a rate and magnitude of plutonium recycle uniformly over the nine global regions; and b) Case F adjusts the MOX-recycle exponentiation time and final (region-averaged) MOX core fraction on a regional basis in a way that assures each regional inventory of accumulated (spent-fuel) plutonium remains positive. Without this local "tailoring" of MOX recycle fraction, local plutonium demands must be satisfied from plutonium excesses in other global regions; details of this "plutonium trade" on a world market (and the proliferation risks related thereto) remain for future elaboration of the relatively "top-level" plutonium inventory model presently being used.

The global inventories of plutonium in the accumulated (spent-fuel), reactor, and separated (reprocessing and fuel-fabrication) forms are shown as a function of time for the BAU Case A (no recycle) and the regionally uniform recycle Case E [40-yr exponentiation time to a final (average) MOX core fraction of 0.15] in Fig. 14. The decrease in

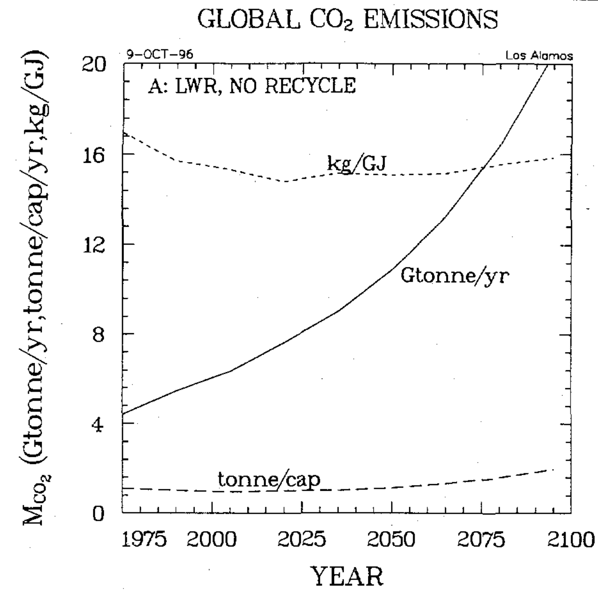


Figure 13. Global carbon emissions in the form of carbon dioxide for the BAU Case A.

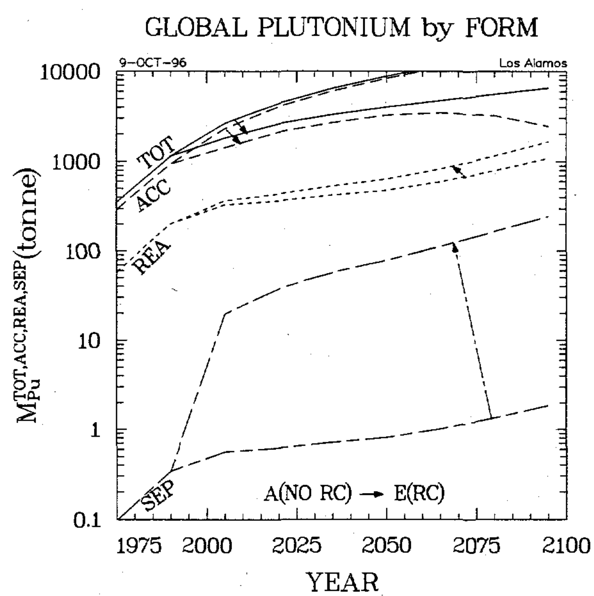


Figure 14. Time dependencies of global plutonium inventories (TOT ⇒ total; ACC ⇒ accumulated in all spent-fuel forms; REA ⇒ active reactor inventories; SEP ⇒ separated in both reprocessing and fuel-fabrication facilities), showing impact of LWR recycle applied uniformly across all global regions for a final MOX core fraction $f_{MOXf} = 0.15$ and the exponentiation time $\tau_{MOX} = 40$ yr (Case E).

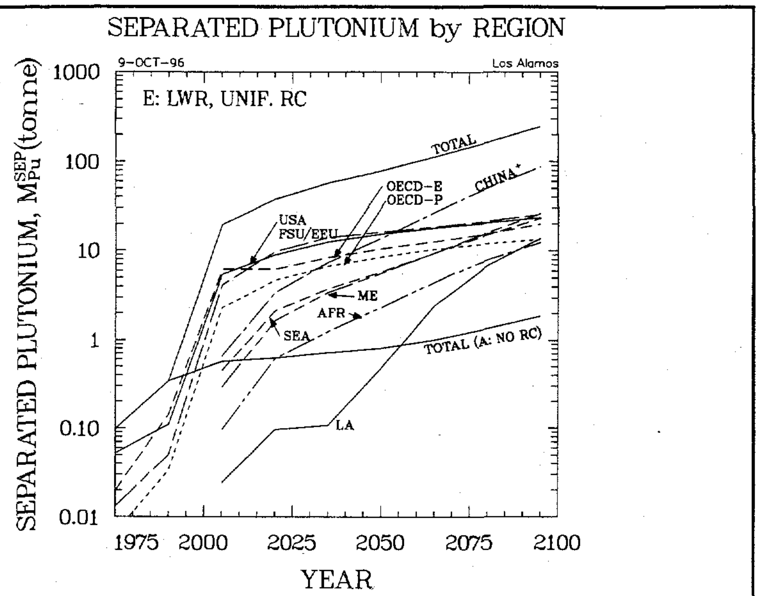


Figure 15. Time and regional dependencies of separated plutonium material streams for Case E (LWR, regionally uniform plutonium recycle).

total global plutonium inventory results from a balance in decreased plutonium in spent fuel *versus* increases in reactor and separated (reprocessing and fuel fabrication) plutonium. The small amount of separated plutonium for the BAU Case A reflects the small but non-zero value used for the initial MOX core fraction. Figure 15 gives the regional distribution of separated plutonium as a function of time.

With the non-zero inventories of separated [reprocessing (SPU) and fuel fabrication (MOX)] plutonium in Cases E or F, the (proliferator's) utilities related to proliferation evolve in time with a more varied dependence on material-stream inventories. For the inventory dependencies used[21], a shift in the material stream having the maximum utility from accumulated (SFT) to reprocessing (SPU), and eventually (≥ 2100) to fuel-fabrication (MOX) material streams occurs. For the 2 %/yr discounting of proliferator utility used, however, the SFT material stream dominates the PRI over the time period considered for this USA region. For this reason, as well as the closeness of the stream utilities in the out years, the weighting used to generate global proliferations utilities and PRIs show little difference between the Case A, E, and F plutonium recycle strategies, as is indicated on Fig. 12.

3. Carbon Tax

The economically optimal implementation of energy taxes in general, and carbon taxes in particular, is complex and not necessarily unique. The carbon-tax Case C (Table I) applies a carbon tax uniformly to each global region. This taxation algorithm starts in the year 2005 and uniformly applies a fossil-fuel charge that increases at a rate of 40 \$/tonneC per 15-year computational time interval. The ratio of carbon emitted per unit energy generated varies for a given fossil fuel[8,12]. The illustrative example reported herein ignores important issues related to[57]: a) revenue recycle (*e.g.*, ways in which tax revenues are reinjected into economies to reduce other distortionary taxes like personal income, corporate, or payroll taxes); b) subsidy removal (which in 1990 amounted to 215 B\$, and the elimination of which would reduce carbon emission by 20% in subsidized countries and worldwide by 7%[56,57]); c) and the trading of emission "rights" in a way that levels the marginal cost of GHG reduction across the globe.

The imposition of a (fossil-fuel-specific) carbon tax and the resulting increase in fossil-fuel prices has three effects: a) decrease the used of fossil fuels; b) increase the market share of more expensive, reduced-carbon or non-fossil energy sources; and c) decrease the regional and global GNP. A comparison of the counterpart to Fig. 8 with carbon taxes applied shows both a decrease in total energy consumption, a decrease in the most egregious carbon-emitting fuel (coal), an increased use of more-expensive but reduced carbon-emitting oil and gas, and increases in nuclear and the more-expensive solar energy sources.

The use of more-expensive energy by the (heavily) carbon-taxed world results in a decrease in the GNP, energy intensity (MJ/\$), and GNP *per capita*. Slight shifts in the global distributions or "concentrations" of these parameters also result.[22] The impact of a range of carbon-tax rates on the CO_2 emission rate is shown on Fig. 16,

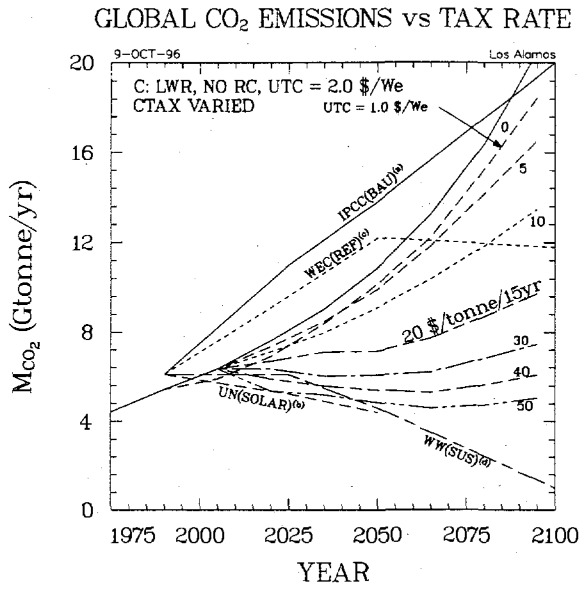


Figure 16. Time dependence of global CO_2 emissions as a function of carbon tax rate (proxy), also showing: a) a range of CO_2-emission scenarios; and b) the impact of reduced NE costs (Fig. 18).

(a) Refs. 51,52; (b) Refs. 52,53,58 and (c) Ref. 53

which includes a number of CO_2-emission scenarios[51-53,58] for comparison. A plot of GNP reduction *versus* CO_2 reduction[22] indicates an increasing sensitivity of GNP as the carbon tax rate is increased to induce greater reductions in CO_2 emissions. The slope or "elasticity" is 0.89 for reductions in CO_2 emission rates below ~20% and increases to 1.53 for the higher rates of CO_2 emission rates induced by the higher taxation rates. The difference in the present value (worth) of the global GNP with and without a carbon tax (*i.e.*, Case A *versus* Case C amounts to ~500 B$ lost from the world economy over the period of the computation, using a discount rate of 4 %/yr. The present value of the (consumption/users) carbon taxes collected at the Case-C rates, however, amounts to ~795 B$; this value does not simply "evaporate" from the world economy, but must condense in a sector(s) not modeled by the ERB model in its present form.

Although the shift in global concentration of economic capability caused by the imposition of a carbon tax is small, such a tax impacts more the developing countries[22]. The impact of this reduced energy usage coupled with the shift to reduce-carbon (oil and gas) or no-carbon (nuclear and solar) energy sources on the CO_2 emission rate is reflected in part by an increased use of NE, which impacts the degree to which the uranium resource is depleted and (ultimately) the need to utilize advance (breeder) fission systems if the NE option is to remain economical.

The benefits of reduced carbon emissions portended by imposition of a carbon tax (if an equitable and/or optimized collection strategy could be devised and implemented) must be balanced by the decreased GNP that results, as well as the increased potential for proliferation risk associated with greater global inventories of nuclear-explosive materials. The implications of a reduced GNP, which over the simulation period has a present value that is comparable or even less than the present value of the tax revenues collected, requires further study. The connection between risks associated with proliferation and risks associated with increasing GHG emissions and atmospheric accumulations can be examined though relative changes in an "operating curve" that (for example) relates PRI to the accumulation of carbon dioxide relative to present atmospheric inventories. Recognizing the risks of presenting oversimplified and possibly over-aggregated correlations, Fig. 17 gives the relationship between the global proliferation utility or proliferation-risk index and the cumulative CO_2 parameter $M_{CO_2}/M_{CO_2,1990}$ for both the BAU Case A (no plutonium recycle, no carbon tax) and Case C (no plutonium recycle, carbon tax). The imposition of a carbon tax (*e.g.*, Case A $\rightarrow$ Case C) results in a large decrease in this GHG risk metric parameter for a relatively small change in the proliferation-risk index. An examination of the time evolution of the fractional increase in PRI *versus* the fractional decrease in $M_{CO_2}/M_{CO_2,1990}$ give[22] a $\partial \ln PRI/\partial \ln GHG$ "elasticity" that is -0.73 up to ~2050, and becomes 0.33 for times greater than 2065. The correlation depicted in Fig. 17 presents an opportunity to mislead if it is not recognized that the increased NE market share (and proliferation risk) results from fossil energy becoming

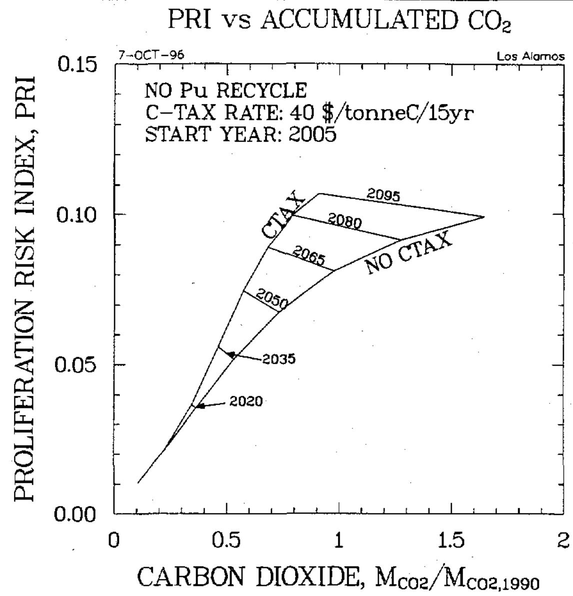


Figure 17. Connectivity of risks metrics related to GHG emission and proliferation based on a Case A (BAU, no recycle, no carbon tax) *versus* Case C (BAU with carbon tax) comparison.

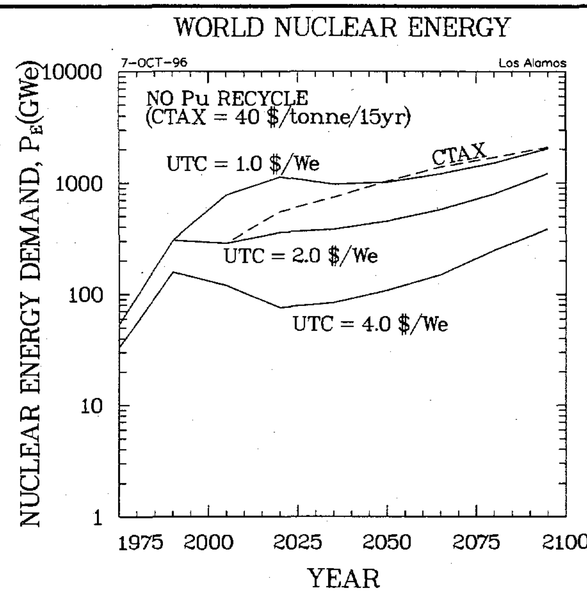


Figure 18. Impact of increased NE costs (Case B) or increased fossil-fuel prices (*vis á vis* a carbon tax, Case C) on the NE global market share (all cases are without plutonium recycle, Table I); also shown is the impact of decreased NE cost.

more expensive *vis á vis* the carbon tax and not as a result of any inherent economic attractiveness of NE; the reduction of $M_{CO_2}/M_{CO_2,1990}$ shown on Fig. 17 results from the carbon tax and reduced overall energy consumption and not because NE is assuming a larger market share. Lastly, irrespective of the driver, a means to translate these relative risk metrics into a relative "consequence space" is required before quantitative conclusions can be made on relative benefits *versus* cost related to nuclear (proliferation) and fossil (GHG impacts) fuels.

4. Nuclear Energy Costs

In the previous section, the market share for NE increased if the cost of fossil fuels is increased by the imposition of a carbon tax. The NE market share and composition (*e.g.*, LWR *versus* LMR) can also be shifted through changes in capital and fuel charges related directly to NE. In a sense, the impacts described on Fig. 16 cast the carbon tax into a role of proxy by which the costs of implementing CO_2-reducing technologies can be related to a given level of carbon dioxide mitigation without the actual imposition of a carbon-tax *per se*. This mode of assessment has been reported for a biomass-sustained hydrogen economy[12], and a similar analysis remains to be developed for NE (in the presence of and in competition with other sustainable energy supplies). Reference 22 describes the impact of NE economics in three areas: a) capital cost of LWRs; b) capital cost of advanced systems, like the LMR; and c) the cost of uranium *versus* accumulated consumption. Only results from the capital-cost variations are reported here.

a. LWR Capital Cost

The impact on NE market demand of increases or decreases in the unit total cost for LWRs (UTC_{LWR} = 2.O $/We, conservative depletion model for uranium costs[28,59]) is illustrated in Fig. 18. All other NE unit costs remain as listed in Table II. A doubling of UTC_{LWR} decreases the global market share by a factor of ~4. The impact of this increased NE cost on GHG emission is relatively small; a similar finding emerges upon decreasing the cost of NE, as is shown on Fig. 18. In terms of total primary energy, NE contributes at most 7-9% of the global primary energy requirements (according to Ref. 45, 5.0% in 1990 and 5.9% in 2020, which differ somewhat from the ERB projections). For NE to impact CO_2 emissions significantly (through the aforementioned carbon-tax proxy), non-electric applications (*e.g.*, process heat and/or electric power for hydrogen generation, for eventual use in the transportation end-use sector) must be considered. Generally, while high carbon taxes bode well for NEs market share, low NE electric-generation costs have little impact on global GHG emissions.

b. LMR Capital Cost

Heretofore, a large ratio of LMR to LWR unit total cost has been imposed (UTC_{LMR}/UTC_{LWR} = 2.0) to insure for computational purposes that the LMR would not be economically competitive with the LWRs, even for the conservative resource-depletion model used to estimate uranium prices[28,59]. Imposition of a strong carbon tax could allow the introduction of additional LWR-based NE to such an extent that the depletion of uranium fuel strongly drives upward the price of uranium. The attendant increase in uranium prices, even with inventory-constrained plutonium recycle to LWRs, could allow the LMR to become competitive in the time frame of interest (*e.g.*, before 2100) if UTC_{LMR} was sufficiently low. Decreasing UTC_{LMR}/UTC_{LWR} to 1.3 while simultaneously imposing a strong carbon tax defines Case D. These conditions, along with the use of a pure depletion model for the uranium resource and cost, was sufficient for the LMR to become economically competitive by the year 2050. Figure 19 gives the fraction of global NE provided by LWRs as a function of time. A technology diffusion model[60] was used to limit the rate of LMR introduction to below that dictated by purely economic consideration; Fig. 19 gives both economics and technology-diffusion LMR introduction rates. The plutonium requirements for Case D are such that the global plutonium inventories stored in spent fuel become depleted by the year ~2065 for the introduction of high-inventory LMRs having unit breeding ratios. The impact of reducing the unit cost of uranium by a factor of two relative to the conservative resource-depletion model used in the base case is also shown on Fig. 19.

Generally, in the context of the ERB forced-economic-equilibrium model, the cheaper the fuel resource, the more of it will be used. Since the cost of uranium remains a relatively small part of the overall cost of NE, however, the

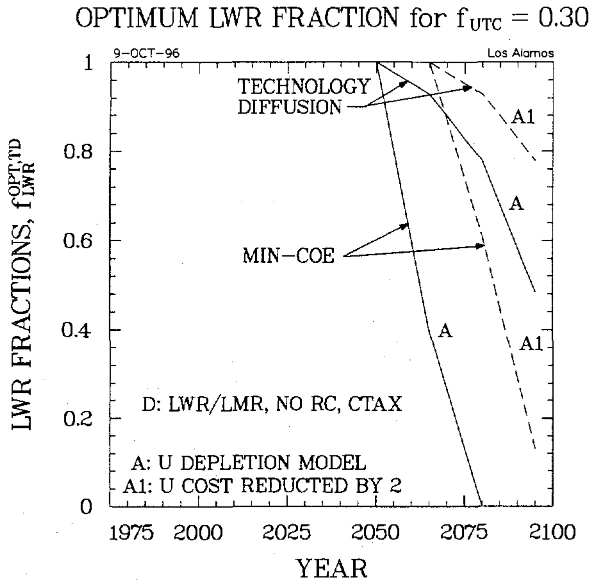


Figure 19. Market penetration of advanced (breeder) reactor under favorable Case D economic conditions (*e.g.*, conservative uranium-resource depletion model, competitive LMR costs relative to LWR base case, high carbon taxes).

impact of reduced uranium charges on the overall market share for NE remains small; a decrease in uranium prices by nearly a factor of eight over the base-case parameters results in less than a doubling of the NE capacity over the BAU Case A by the year 2100. The factor of ~8 reduction on uranium cost over that predicted by the resource-depletion model used herein gives a cost-*versus*-usage relationship that is similar to the one used in a recent study of the LMR[55]. Hence, with twice the base-case uranium-resource prices, the LMR under the Case-D conditions (strong carbon tax, UTC_{LMR}/UTC_{LWR} = 1.3) does not become economic until ≳ 2065; a reduction in uranium-cost *versus* resource relationship by a factor of ~8 stalls the LMR introduction to some time beyond the year 2100, based solely on economic (including resource) considerations.

It should be noted that the rudimentary NM balance presently used in the NE part of the ERB model fixes the LMR breeding ratio (BR = 1.0 in the cases reported here, Table II). Introduction of the high-specific-inventory LMRs at the economically driven, technology-diffusion-limited rates quickly depletes the accumulated (*e.g.*, all spent-fuel forms) plutonium inventories, and with the present level of NM "feedback", the global inventory of available plutonium goes to zero. This decrease combines with the reduced inventory of separated plutonium (the LMR is assumed to have a close-coupled, low-inventory reprocessing plant) actually diminishes the PRI, as most of the global plutonium is shift to (assumed) "safe and secure" in-reactor inventories.

V. SUMMARY CONCLUSIONS

A global E^3 (energy/economics/environmental) model[8,12] has been adapted with an NE/NM model in an effort to understand better "top-level", long-term trade offs between civilian nuclear power, nuclear-weapons proliferation, fossil-fuel burning, and long-term global economic welfare. Using a BAU point-of-departure case, economic, resource, and proliferation-risk implications of plutonium recycle in LWRs, greenhouse-gas-mitigating carbon taxes, and a range of NE (capital and fuel) cost considerations have been examined. The parametric variations about the BAU base case are presented in the spirit of preliminary examples to provide vehicles for early critical review and comment. On the basis of these preliminary results it is concluded that, while GHG mitigation through some form of carbon taxation may increase the NE market share (as well as that for solar and other renewable energy sources), significant impacts of NE on the GHG problem will occur only if cost-competitive non-electric applications of NE are emphasized. Additionally, under conditions where in-reactor plutonium inventories can be considered "safe-and-secure", introduction of LMRs can lead to significant reductions in PRI, particularly if accompanied by a closely coupled integral fuel cycle.

This study has identified important model limitations that require bounding, study, and development, a few of which are listed below:

- Although a proliferation-risk metric has been evaluated in conjunction with a GHG-reduction metric, the crucial connection to "consequence space" remains to be made;

- The (subjective) MAU-based proliferation model provides a useful analytical structure, but bases for utility-function and weighting choices must be evaluated/elaborated; feedback mechanisms between NWA, ENV, and SANC parameters (Fig. 5) and proliferator utilities remain to be formulated;

- A focus for proliferation risk that is broader than the present inventory-based civilian fuel cycle needs to be developed; comparisons of proliferation risks associated with other sources of NW-usable material must be made (*e.g.*, HEU, Fig. 5), as well as the other four prliferation drivers listed in Fig. 4;

- The use of the carbon-tax proxy as a means to assess the cost *versus* benefit of sustainable, GHG-reducing energy technologies, as well as technology-diffusion limiting introduction rates of these technologies require considerable modelistic development and benchmarking;

- Metrics that relate energy security to national security need to be developed, along with the introduction of rudimentary measures of political/economic stability, and related risks (*e.g.*, NW accessibility as well as long-term capital availability; impacts of regional environmental, and resource limits on growth in human welfare, *etc.*)

- Improved geographical resolution, at least insofar as access to and assessment of each of the three fundamental choices available to address E^3 issues is concerned (*e.g.*, doing without; doing it better; doing it differently)[61]; develop and implement economic elements that differentiate elements between decentralized and centralized economies.

The above list will provide guidance for future work on the analytic capabilities being developed to support the Los Alamos Nuclear Visions Project.

NOMENCLATURE

ACC	accumulated plutonium (as spent fuel in all forms)
AFR	Africa
ANS	American Nuclear Society
ASI	Advanced Science Institute (NATO series)
APU	accumulated plutonium (as spent fuel in all forms)
ATW	accelerator transmutation of (nuclear) waste
BAU	business as usual
BE	backend of fuel cycle
BN	actinide/fission-product burner
BR	breeder LMR
BU(GWd/tonne)	fuel burnup
BU25	^{235}U burnup
CE	uranium conversion/enrichment
CISA	Center for International Security Analysis
COE(mill/kWeh)	cost of electricity
CRT	criticality hazard
CSF	cooling for spent fuel
CST	cost
CST_{MAR}	marginal cost
CST_{TOT}	total cost
CV	ore $\rightarrow$ UF_6 conversion
D	detection (of proliferation action)
D&D	decommission and decontamination
DT(yr)	development time for NW capability
E^3	economics/energy/environmental
EEU	eastern Europe
ENV	political environment
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ER	enrichment
ERB	Edmonds/Reilly/Barns (model)
e	political environment index
FC	fuel cycle
FCR(1/yr)	fixed-charge rate
FE	frontend of fuel cycle
FF	fuel fabrication
FP	fission products
FSU	former Soviet Union
FTW	fusion transmutation of (nuclear) waste
f_{LWR}	fraction nuclear power provided by LWRs
f_{MOX}	MOX core (voilume) fraction
f_{UTC}	UTC cost factor for LMR, $(UTC_{LMR} - UTC_{LWR})/UTC_{LWR}$
GDP	gross domestic product
GHG	greenhouse gases
GNP	gross national product
GR	global region
GRI	Gas Research Institute
HEU	high-enriched uranium
HM	heavy metal (uranium)
IEA	International Energy Agency

IIASA	International Institute for Advanced Systems Analysis
ITD_{MP}	inherent technological difficulty related to materials processing
ITD_{NW}	inherent technological difficulty related to nuclear weapons fabrication
i	material stream index
j	attribute, criteria index
k	fuel cycle index
LEU	low-enriched uranium
LMR	liquid-metal reactor
LP	linear program
LTS	large technical system
LWR	light-water reactor
l	country/region index
M_i(kg)	material inventory in stream i
MA	minor actinides
MAU	multiattribute utility (analysis)
MIT	Massachusetts Institute of Technology
MM	mining and milling
MOX	mixed uranium/plutonium oxide fuel
MP	material processing
MS	monitored storage
m	time index
NE	nuclear energy
NM	nuclear materials
NU	natural uranium
NW	nuclear weapon
NWA	nuclear weapon aspiration level
n	number of assessment criterion, NWA index
O&M	operating and maintenance (costs)
ORAU	Oak Ridge Associated Universities
OT	once-through LWR
P	production function or power
PNL	Battelle Pacific Northwest Laboratory
PRI_i	proliferation risk index for material stream i
PU	plutonium
p_f	availability factor
Q_E	engineering gain or Q-value
R, Rx	reactor
RAD	radiation hazard
RAF	risk-aversion factor
RC	recycle (plutonium)
RCP	plutonium recycle LWR
RCU	uranium recycle LWR
REPRO	reprocessing
RP	risk potential or reprocessing
RPU	reactor plutonium inventory
RU	recycled uranium
r(1/yr)	discount rate
SANC	sanctions
SCI	science
SEI	Stockholm Environmental Institute
SEP	separated plutonium (reprocessing and/or fuel fabrication)
SF	spent fuel

SF_{NEW}	"fresh" spent fuel
SF_{STR}	spent fuel in short-term (~15-20 years) storage
SF_{RPC}	spent fuel in closed (sealed) repository
SF_{RPO}	spent fuel in open (operating) repository
SFT	total spent fuel
SI(kg/MWt)	specific inventory
SNM	special nuclear material
SOI	status of information
SPU	separated plutonium
STR	storage
SW	separative work
TR	transport
T_{MOX}(yr)	half time for MOX introduction
TEC	technology
TH	thermal
t(yr)	time
UC_j($/unit)	unit cost of j^{th} item
UNEP	United Nations Energy Project
UTC($/We)	unit total cost
u	(general) utility function
$\langle u \rangle_i(y_i)$	weighted averaged utility function for material stream i
$\langle u \rangle_j(x_j)$	weighted averaged utility function for criterion j
$u_i(y_i)$	separable utility function for material stream i
$u_j(x_j)$	separable utility function for criterion j
$u_{ij}(y_i,x_j)$	component utility function
WP(yr)	warning period (as fraction of project remaining)
WPU	weapons plutonium
w, $w_{ij,i}$	utility function weights, normalized
x_j	mass fraction of j^{th} component
λ_j(1/yr)	time constant for j^{th} process
η_{TH}	thermal conversion efficiency
η_p	plant overall efficiency, $\eta_{TH}(1 - 1/Q_E)$
τ_j(yr)	characteristic (hold-up) time for j^{th} process
v	uranium costing exponent

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