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Author(s):

R. A. Krakowski, J. W. Davidson, C. G. Bathke,
E. D. Arthur, R. L. Wagner, Jr.

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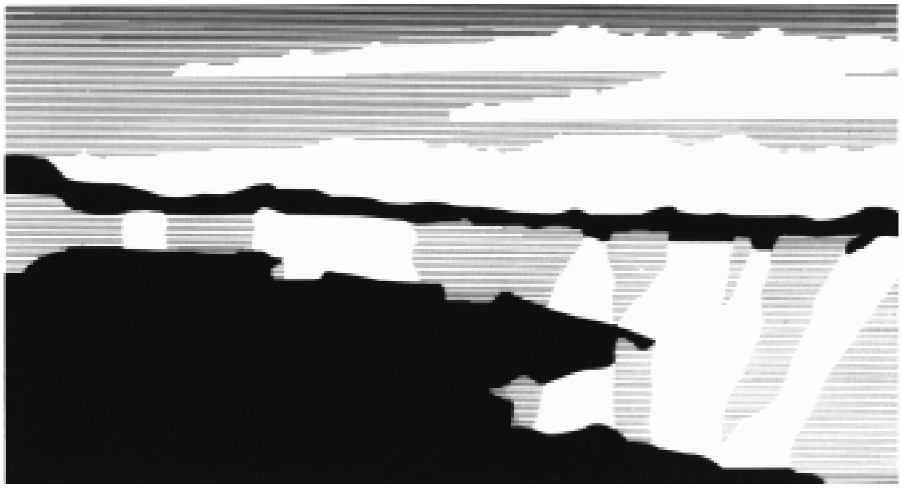

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NUCLEAR ENERGY AND MATERIALS IN THE 21ST CENTURY

R. A. KRAKOWSKI, J. W. DAVIDSON, C. G. BATHKE,
E. D. ARTHUR, R. L. WAGNER, JR.

Systems Engineering and Integration Group, Technology and Safety Assessment Division
Nuclear Materials and Stockpile Management Program
Los Alamos National Laboratory
Los Alamos, New Mexico 87545, USA

ABSTRACT

The Global Nuclear Vision Project at the Los Alamos National Laboratory is examining a range of long-term nuclear energy futures as well as exploring and assessing optimal nuclear fuel-cycle and material strategies. An established global energy, economics, environmental (E^3) model has been adopted and modified with a simplified, but comprehensive and multi-regional, nuclear energy module. Consistent nuclear energy scenarios are constructed, where future demands for nuclear power are projected in price competition with other energy sources under a wide range of long-term (~2100) demographic, economic, policy, and technological drivers. A spectrum of futures is examined at two levels in a hierarchy of scenario attributes in which drivers are either external or internal to nuclear energy. The results reported examine departures from a "basis scenario" and are presented in the following order of increasing specificity: a) definition and parametric variations of the basis scenario; b) comparison of the basis scenario with other recent studies; c) parametric studies that vary upper-level hierarchical scenario attributes (external drivers); and d) variations of the lower-level scenario attributes (internal drivers). Impacts of a range of nuclear fuel-cycle scenarios are reflected back to the higher-level scenario attributes that characterize particular nuclear energy scenarios. Special attention is given to the role of nuclear materials inventories (in magnitude, location, and form) and their contribution to the long-term sustainability of nuclear energy, the future competitiveness of both conventional and advanced nuclear reactors, and proliferation risk.

1. INTRODUCTION

The goal of this study is to advance understanding of regional and long-term impacts of front-end (including reactor) and back-end nuclear fuel-cycle strategies on regional and global market shares assumed by nuclear energy. The evolution of these market shares is determined primarily by an interdependent array of economic (resource, R&D, capital, operating, and environmental costs) and policy (R&D emphases, energy structuring, proliferation concerns, security constraints, *etc.*) choices. These choices are influenced primarily by technological, security, and economic drivers that describe and/or influence the country or region.

Studies of the future and associated forces of change that extend much beyond a generational time horizon are subject increasingly to greater uncertainty. Impacts of these uncertainties are codified though the use of "scenario-building" techniques [1,2], where a spectrum of possible futures is quantified by means of a series of well-defined, simplified, and generally surprise-free assumptions. While an array of alternative futures contributes little to resolving an uncertain future, scenario building often allows quantitative assessment of possible eventualities while offering an improvement to the painting of a single and generally biased (either positively or pessimistically) picture of the future [2]. Furthermore, while generally constructed without specific surprising events, scenarios sensitive to critical economic drivers may offer insights into impacts of unincorporated surprises, if such events can be translated into economic terms.

The attributes of a particular scenario are expressed in terms of a hierarchical structure, at the top of which are demographic variables (population growth, age structure, workforce size and productivity, and inter-regional migrations). Population growth and the striving for improved living conditions for regional populations drive the demand for energy services, which in turn define the demand for secondary (liquids, gases, solids, and electricity) and primary (oil, gas, solids, nuclear, solar, and hydro) energy. Most of the attributes of the nuclear energy scenarios in this study fall into the lower hierarchical echelons, which include in descending order policy, market, and technology. A framework to examine key scenario impacts uses an E^3 model [3] that has been modified to include material-inventory, economic, and nuclear-proliferation characteristics unique to nuclear energy [4].

This study addresses the following two generic questions for nuclear energy:

a) Growth: To what degree is the market share for nuclear energy determined by top-level scenario attributes (population growth, efficiency or energy intensity, environmental factors) and top-level nuclear energy costs (uranium resource, plant capital, operating)?
b) Fuel Cycle: For a given nuclear energy scenario, what are nuclear material inventory (form, quantity, region) impacts and related economic, environmental, and proliferation risks for a range of fuel-cycle options (once-through LWRs, plutonium recycle in thermal-spectrum reactors, advanced fast-spectrum plutonium burners)?

Generally, the first question relates to “external drivers,” and the second question pertains to “internal questions” associated with the future of nuclear energy.

2. APPROACH

This study of a range of possible global nuclear energy futures conforms to a hierarchy of scenario attributes that are evaluated with a modified [4] long-term E^3 model [3] that examines 13 global regions. This section summarizes the hierarchy of scenario attributes used, the model, and a "basis scenario" used as a point-of-departure for sensitivity studies.

2.1. Scenario Hierarchy

Scenarios can be classified as both "descriptive" and/or "normative" [5]. A "descriptive" scenario evolves *via* a rule-based model without significant geopolitical, policy/institutional, economic/market, or technology changes. A "normative" scenario allows for (often interactive) modifications of these respective areas. In the context of the E^3 modeling tool, a "business-as-usual" scenario generally falls into the "descriptive" class, whereas scenarios that are perturbed relative to it exhibit more "normative" characteristics. Recent studies by the World Energy Council (WEC) [6] and by a cooperative effort between the International Institute for Applied Systems Analysis (IIASA) and the WEC [5] are contemporary examples of scenario characterization of long-term, global energy systems.

The two examples of scenario-based studies cited above are ostensibly independent of position on a given approach to providing primary energy. When used to examine possible futures from the viewpoint of a particular energy source, a scenario selection and focusing process occurs in order to emphasize specific roles and niches for the energy source considered. In the case of the IAEA Working Group #2 [7] examination of nuclear reactor and fuel-cycle strategies, three cases were identified as: "High Variant"; "Medium Variant"; and "Low Variant." This selection process is used primarily to examine a range of nuclear energy scenarios and concerns related to uranium resources, fuel-cycle facilities, nuclear-material inventories (location, quantities, and form), and spent-fuel waste. The economics that led to the particular nuclear energy demand scenarios remains relatively frozen in the assumptions of the originating [5] studies. The decoupling that results when an investigation enters the problem far down into a hierarchy of interdependent scenario attributes risks loss of opportunity to understand related tradeoffs. A recasting of the procedure used to generate the scenario attributes embodied in the Ref. [5, 6] studies into a hierarchical format gives more visibility to this potential problem, in addition to providing both a focus and an intercomparability to related studies. Five hierarchical levels for scenario rule/definition-making are defined and elaborated in Ref. [8].

2.2. Global Economics/Energy/Environmental (E^3) Model

2.2.1. Overview

The ERB (Edmonds, Reilly, Barns) model [3] is based on a behavioral market equilibrium that internally balances energy production and usage and is comprised of four main parts: supply, demand, energy balance, and greenhouse gas emissions. 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); and solar (excluding biomass; including solar electric, wind, tidal, ocean thermal, fusion, and advanced renewable; solar thermal is included as a form of energy conservation). The energy-balance module ensures that supply equals demand in each global region, with electrical energy being generated and used only within a given global region. Energy and economic (market-clearing) balances are performed for 13 global regions at nine 15-year steps covering the period from 1975 to 2095. Energy balance across regions is established by a set of rules [3] for choosing the respective prices and price scalings that are required for supply to equal demand in each energy-service group for each fuel.

The demand for energy services in each global region is determined by: the cost of providing these services; level of income (~GNP); and regional population and top-level demographics. Energy services are fueled by an array of four secondary fuels (liquids, gases, solids, and electricity). The mix of these secondary fuels used to provide a given energy service is determined by a cost-based market-share algorithm [3], as is the demand for fuels used to produce electricity and the share of oil and gas provided by transformation of coal and biomass. The tracking of primary energy to secondary energy sources to energy services transformation is modeled using a Leontief-type formulation. The energy demand module also maintains a set of energy flow accounts. The energy supply module estimates: a) the supplies for all regions and fossil fuel forms that provide the basis for (iterating) world (fossil-fuel) prices; b) the cumulative usage; c) and the cost of recovery (including environmental costs) at one of five resource grades. Energy supplies are disaggregated into two categories: renewable (hydro, solar, biomass, and nuclear breeder) and non-renewable (conventional and unconventional oil, natural gas, coal, and non-breeding nuclear). A given resource is active and able to contribute to demand only if the primary energy price delivered to the energy supply module exceeds the production cost, and if the resource has not been exhausted.

2.2.2. Nuclear Model

The nuclear model developed and operated “under” the ERB model [9] performs three primary functions:

a) It determines a “top-level” cost estimate in terms of a cost of electricity, COE(mill/kWeh), that is reformed into the Leontief coefficients used in ERB to estimate market shares.
b) It tracks the flow of key nuclear materials throughout the nuclear fuel cycle (natural uranium, low-enriched uranium, plutonium, and spent fuel) for use in nuclear materials and proliferation-risk assessments.
c) It performs a multi-attribute utility analysis of proliferation risk [10–12] from the civilian fuel cycle.

The uranium resource model originally used in ERB [3], for purposes of the present study, has been replaced with that of Ref. [13], as interpreted in Ref. [14].

The nuclear model is based only on the uranium/plutonium cycle, as utilized in each global region at each time interval by an economically determined mix of light water reactors (LWR) and breeder reactor systems. The LWRs in a given global region operate along an exogenously enforced trajectory of MOX-recycle core fractions, as is described in Section 3.2.3. The breeder system, if economics and technology diffusion time constraints allow, is introduced with a preassigned breeding ratio. In the present version of the model, plutonium is assumed to flow freely between global regions as needed, where deficits in LWR-usable material arising in some regions are assumed to be corrected by flows from regions with excess (LWR-usable) plutonium.

Costing of nuclear energy is based on a top-level, highly aggregated algorithm [9] that accounts for annual capital charges, annual plant operating and maintenance charges, and annual charges related directly to the nuclear fuel cycle. The component of the COE related to the plant capital costs is expressed in terms of a fixed charge rate and a unit total cost, UTC($/We), while annual operating charges are expressed as a fraction of the total capital cost of the power plant. Differences in COE between LWRs and breeders are reflected primarily in differences in the respective unit total cost values and that part of the COE related to the fuel cycle [9]. For each global region and time interval, the COE-minimizing fraction of nuclear energy delivered by LWRs (for a given MOX recycle fraction) is determined, and an LWR-breeder reactor composite price is returned to the ERB demand module for evaluation of the respective market share for that particular region and (iterated) market-clearing world fossil-fuel price.

The nuclear fuel cycle is described in terms of the following sequence of processes: mining and milling of uranium; conversion of uranium oxide to the volatile fluoride; isotopic enrichment; fuel fabrication; fissioning in reactor; spent fuel cooling and storage; reprocessing; and repository storage directly as spent fuel or as separated fission products and minor actinides. The simplified species-resolved mass balances, based on input-output analysis [15], are used to model regional and temporal material flows. Unit and operating costs are applied to each of these processes, from which a fuel-cycle cost for the entire system (LWRs plus breeder reactors) is determined. Plutonium flows and accumulations are monitored for each global region as a function of time, with reactor plutonium, separated plutonium in reprocessing and fuel fabrication, and accumulated plutonium in spent fuel (differentiated into LWR-recyclable or non-recyclable forms) being the four major categories tracked.

2.2.3. Basis Scenario

The primary function of the “basis scenario” is to provide a point-of-departure to which shifts from upper-level or lower-level hierarchical variations can be referenced. The basis scenario reflects a “most probable future,” albeit uncertainties are great and “projections” *per se* are not intended. Major forces behind total primary energy demand are population growth, workforce makeup and productivity as it drives GNP growth, and the efficiency with which primary energy is converted to secondary energy and ultimately to the provision of energy services. These top-level scenario attributes are inter-related in a way that is not captured by most long-term E^3 models. While these top-level scenario attributes strongly impact energy demand, that part of the demand potentially served by nuclear energy is determined in competition with alternative sources through economic, environmental, and policy choices made further down the hierarchical chain described above and elaborated in Ref. [8]. The adaptation of a generalized scenario attribute hierarchy to the problem at hand is illustrated in Table I, which serves as a “roadmap” for this study, in so far as the upper-level attributes are concerned.

The top-level scenario attributes that characterize the basis scenario use the data base (with some modification) from an application of the ERB model to understanding the economics of carbon-dioxide emission control [3,16-18]. The population data base originally used in ERB was shifted upward (by ~10%, depending on the region) to reflect recent U.N. projections [5, 6]. The GNP projections begin with base-year (1975) values, and then scale subsequent years according to population growths, workforce productivity increases, and energy service prices. The exogenously determined productivity increases were left unaltered from the original ERB data base. Energy intensity is specified through improvements in efficiencies that relate energy service demands to the amounts of secondary energy needed to meet these demands. The ~1%/year decrease in the ratio of energy service to secondary energy is used in this study to define the basis scenario. The relationship between cost and fossil fuels grade was used without modification in this study, but the uranium resource cost *versus* grade relationship given in Ref. [13] replaces that originally used in ERB [3]. Taxes and tariffs, as reported in the ERB model, remain unchanged. The main taxation variation was that applied at the consumption level to stem atmospheric carbon emissions; for the basis scenario, the carbon tax is zero. Reference [8] provides key nuclear energy parameters used to perform nuclear materials balances and to determine market shares for the basis scenario and subsequent scenario variations.

To simplify data displays and to facilitate comparisons with other studies [5–7], the 13 regions have been aggregated into three macro-regions, as was done in Ref. [5]: industrialized countries (US, Canada, OECD-Europe, OECD-Pacific); reforming economies (eastern Europe, former Soviet Union); and developing countries (China, southeast Asia, India, Latin America, northern and southern Africa, Middle East). Comparisons of total primary energy and total nuclear energy projections with WEC results [5, 6] *via* the IAEA study [7] are reported in Figs. 1a and 1b. Aggregated growth rates of GNP, primary energy, and energy intensity also compare favorably [8].

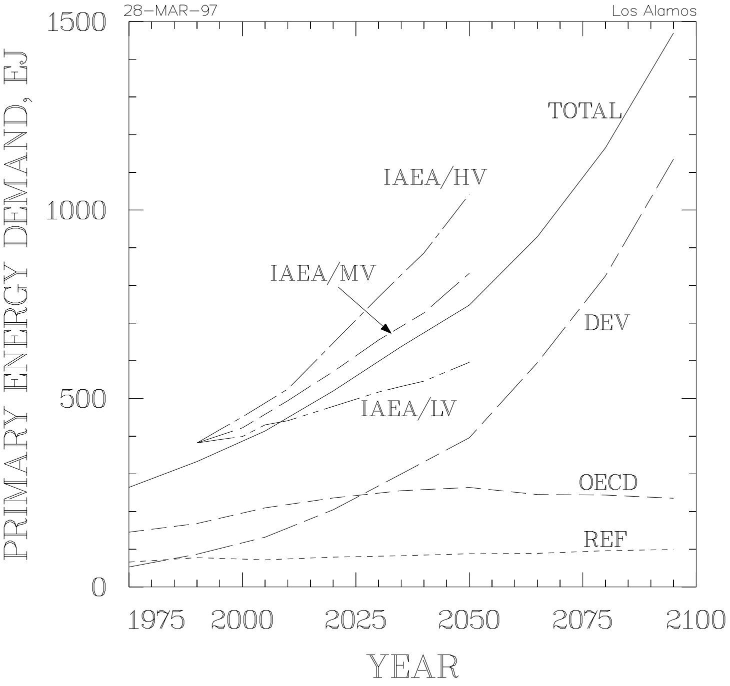

Figure 1a. Evolution of aggregated total primary energy for the basis scenario; a comparison is made with the Ref. [7] high (HV), medium (MV), and low (LV) variants, as adopted from the WEC/IIASA [5] study.

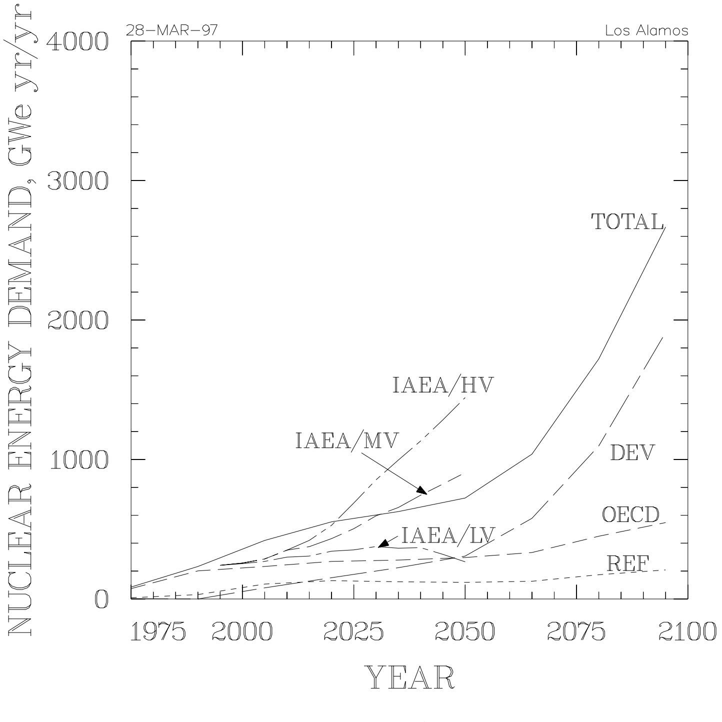

Figure 1b. Aggregated nuclear energy growth rates for the basis scenario; a comparison is made with the Ref. [7] high (HV), medium (MV), and low (LV) variants.

3. RESULTS

The results presented in this section are based on departures from the basis scenario and are divided into two broad categories: external drivers (variations in upper-level parts of the scenario attribute hierarchy that are considered "predetermined conditions" [1]); and internal drivers (variations in attributes that reside at the lower rungs of that hierarchy and are characterized as "critical uncertainties" [1]). Departures from the basis scenario nuclear energy demand are caused by changes in these upper-level attributes. Sensitivities of demand to these upper-level attributes are first reported. The "departure" scenarios that result from variations in these external drivers provide the basis for a range of nuclear energy demand variants that parallel those reported in Ref. [7]. The impacts of drivers that are internal to nuclear energy (scenario attributes that are lower in the scenario attribute hierarchy) on the choice of optimal nuclear fuel-cycle strategies and the relationship of these choices to the external drivers are examined for both the basis scenario and for a range of departure scenarios.

3.1. Upper-Level Hierarchial Variations: Impacts of External Drivers

The five external drivers (population, GNP, energy intensity, taxes, and nuclear economics) are combined with the top-level economic parameters [capital and (uranium) resource costs] to define the main "external drivers" that are varied to explore possible nuclear energy demand scenarios. All upper-hierarchical variations are single-point perturbations about the basis scenario, which is characterized by a once-through LWR fuel cycle.

3.1.1. Population

The basis scenario and most of the related departure scenarios follow the U.N. population projections that predict nearly 12 billion persons on earth by the year 2100. Adjusting [8] regional asymptotic population levels used to model regional population growth in the modified model gives ~±17% variations in world populations in 2100 relative to the U.N. projections. These single-point population variation were made without adjustments to the base (1975) GNP used in the ERB model. Figure 2 shows results of population variations.

3.1.2. Workforce Productivity

The ERB model adjusts a base regional GNP in time for: population increase; an aggregated price for energy services using region-dependent price elasticities; and an increase in workforce productivity, which is expressed as a region- and time-dependent rate of annual productivity enhancement. The impact of region-independent increases and decreases in productivity by ~±20% on GNP was examined. This productivity reflects evolving workforce percentage (of total population), age distribution, and skill levels, all of which show strong regional dependencies. The impacts of these GNP variations on nuclear energy demand are shown in Fig. 3. These impacts on energy demand, for the income elasticities used in the ERB model, are much greater than that for single-point population variations (Fig. 2) alone.

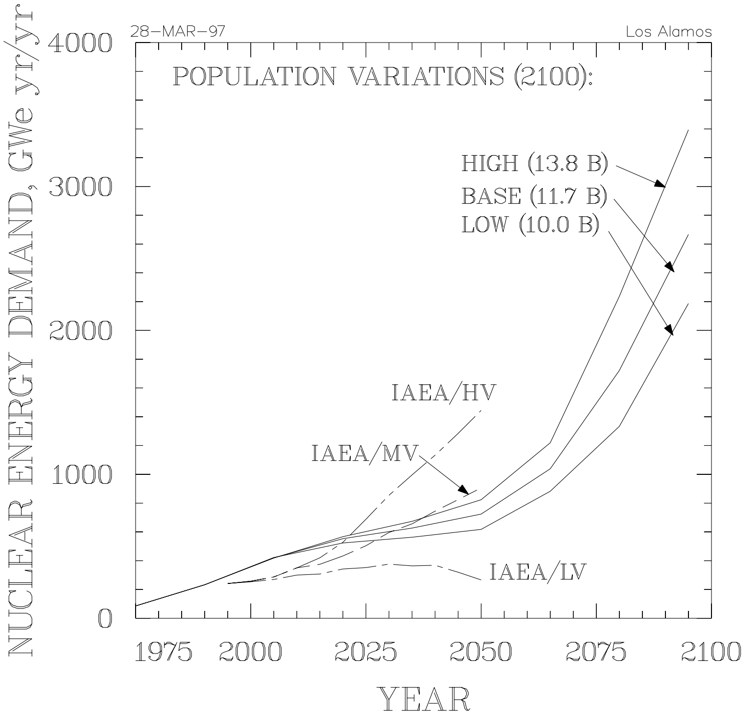

Figure 2. Impact of population variations on nuclear energy demand; comparison with Ref.[7] scenarios is given.

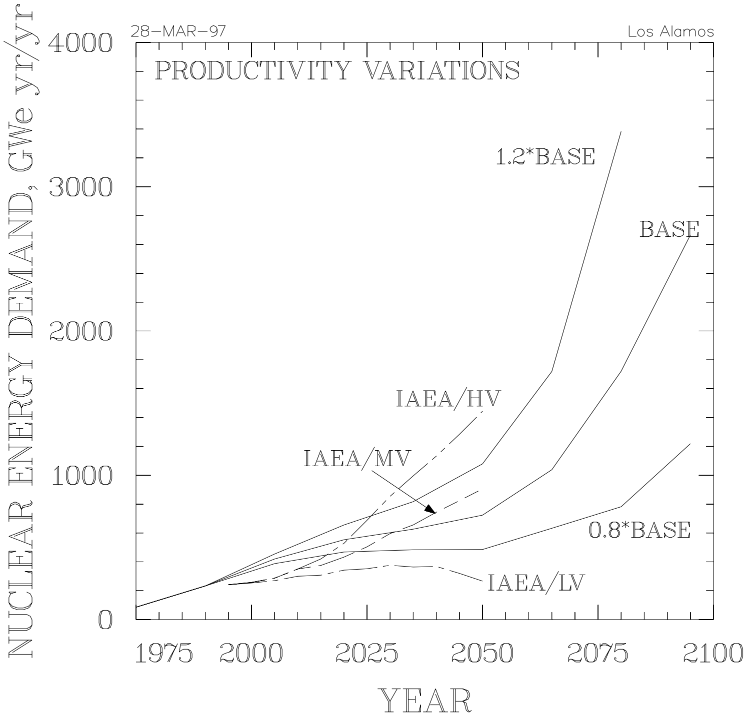

Figure 3. Impact of workforce productivity (GNP) on total nuclear energy demand; comparison with Ref.[7] is given.

3.1.3. Energy Intensity (End-Use Efficiency)

The ERB model varies (primary- or secondary-) energy intensity indirectly through a technology improvement rate that relates an ever decreasing secondary-energy requirement needed to satisfy a given demand for energy service. The basis scenario uses a regionally dependent technology improvement rate of ~1.0%/year, which is unchanged from that in the original ERB data base. Generally, the decrease in the primary-to-secondary energy conversion efficiency *versus* time is a result of regional populations demanding higher forms of energy (liquids and electricity) to meet the energy service demands of a growing population that experiences increasing wealth. The impacts of a range of technology improvement rates on the demand for nuclear energy is shown in comparison to the Ref. [7] demand scenarios in Fig. 4. A technology improvement rate as high as ~1.5-2.0%/year closely tracks the "ecologically driven" low-variant scenario of Ref. [7], whereas the technology improvement rate must fall to ~0.5%/year to reproduce the high-variant case reported in Ref. [7].

3.1.4. Carbon Tax

The imposition of a carbon tax has the effect of increasing the cost of fossil fuels (particularly coal), decreasing total energy use and GNP (somewhat), and increasing the market share for reduced- or zero-carbon energy sources. The impact of applying a strong carbon tax rate (40 \$/tonneC/15yr) on the demand for nuclear energy is shown on Fig. 5. This carbon tax rate stabilizes total carbon emission to values associated with the year of implementation [8]. Halving this rate produces global carbon emissions that are significantly higher (> 50%), but these emissions are a factor of two lower than for the basis scenario of no tax. For these and the basis scenario, biomass is priced high and does not become a major contributor to the primary energy demand, although the impacts of reduced biomass costs have been reported [17].

3.1.5. Nuclear Economics

Although the details of nuclear energy cost logically should be treated as an "internal driver," for the purposes of this study and the focus given to nuclear fuel-cycle internal drivers, the capital and resource costs associated with nuclear energy are included as a "borderline external driver."

3.1.5.1. Capital Cost. For the uranium resource model used and the unit costs associated with the once-through LWR fuel cycle [8], the capital cost is the main component of the COE for nuclear power and, hence, the main determinant of market share returned by the ERB model. The capital cost is embodied in a single variable - the unit total cost, UTC(\$/We). The basis scenario adjusted this cost for 1975 and 1990 in relevant regions so that the model returned an annual nuclear energy generation that approximated historical values. These unit cost values typically are in the range 1.5-2.0 \$/We. The basis scenario then increased this cost over the period 2005-2095 to achieve an asymptote of 2.4 \$/We. The impacts of increasing or decreasing this

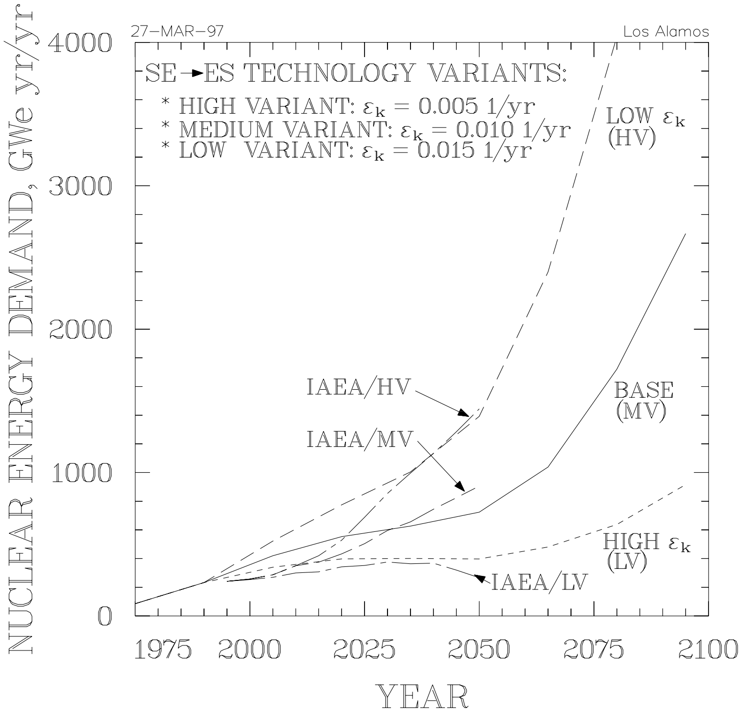

Figure 4. Impact of energy-service technology improvement (ε_k) on nuclear energy demand, and comparison with Ref. [7]; the $\varepsilon_k = 0.005, 0.01,$ and 0.015 1/yr cases[8] create high, medium (basis-scenario) and low variants on nuclear energy demand.

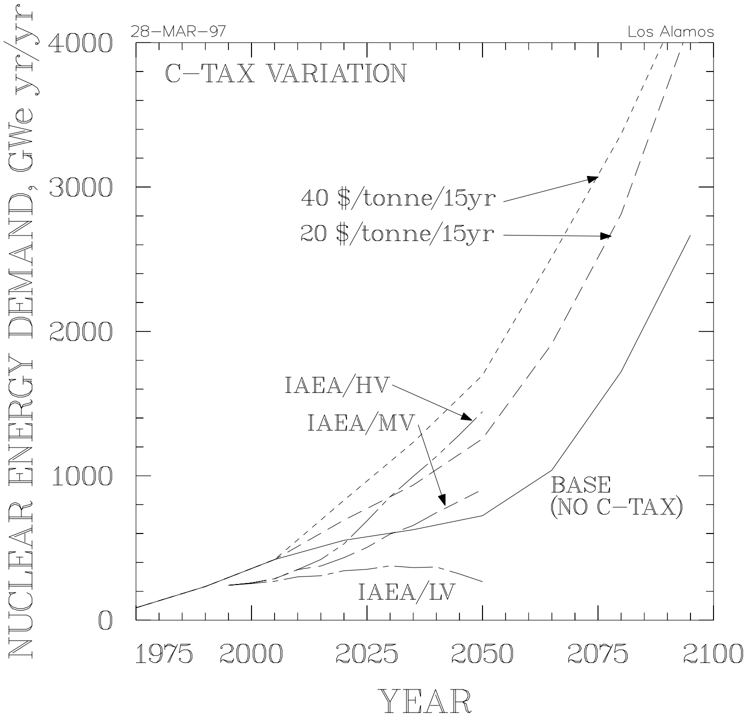

Figure 5. Impact of carbon taxes on nuclear energy demand; comparison with Ref.[7] is given.

asymptote to 3.0 or 2.0 $/We, respectively, are shown in Fig. 6. All regions were treated equally for times greater than 2005. The impact of these unit cost variations on atmospheric carbon emissions is small [8] compared to the imposition of carbon taxes. Generally carbon taxation creates a favorable environment for nuclear energy growth with reductions in GHG emissions, but the cost-driven increase or decrease in nuclear energy demand alone has little impact on GHG emissions.

3.1.5.2 Uranium Resource. The relationship between uranium resource grade, resource amount, and cost [13, 14] is used to provide the scaling of unit cost with accumulated uranium use. The basis scenario assumes that the Known Resources category [13] describes reality. The weight fraction of ^{235}U in tailings is determined by the minimum cost conditions [15, 19] for the relative values of mined/milled uranium unit cost and a chosen unit cost of enrichment [8]. A minimum price of 100 $/kgU for mined/milled uranium is enforced for all resource categories, and the optimum-cost tailings fraction (normally 0.23 weight percent, but decreasing for more conservative resource assumptions [8]) is used in all cases.

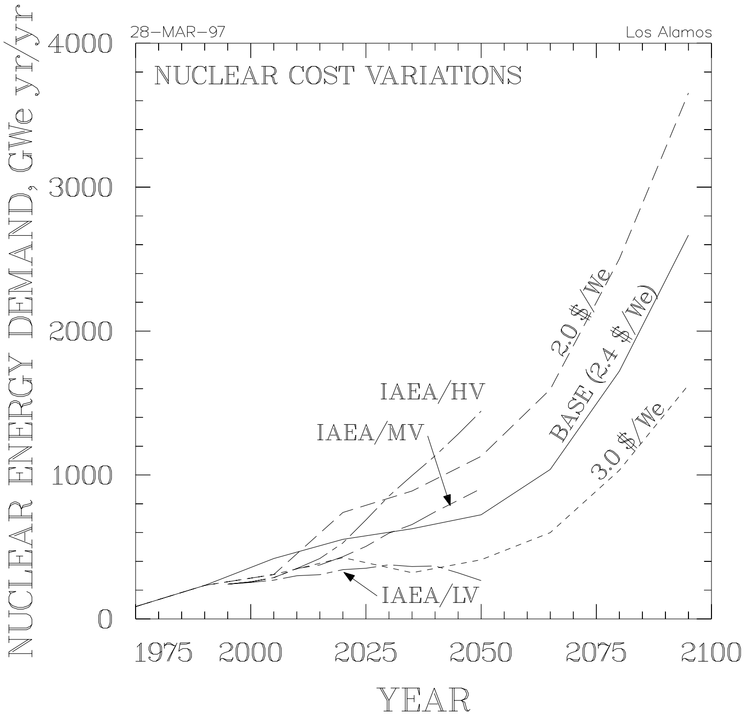

Figure 6. Impact of nuclear energy capital costs on nuclear energy demand; comparison with Ref.[7] is given.

The dependence of uranium usage, unit cost, and optimal enrichment on time and uranium resource assumption is described in Ref. [8]. For both Known Resource and the Total Resource categories [13, 14], uranium costs remain at the threshold price for the basis scenario nuclear energy demand, although a departure from the threshold price beyond ~ 2080 for the basis scenario (once-through LWR, Known Resource) is observed. The Conventional Resource category shows an increase in uranium prices after the year 2050 for the basis scenario nuclear energy demand, with these increased uranium prices resulting in a decreased nuclear energy demand and reduced uranium consumption. These decreases are small and occur only after 2070. Earlier studies using the ERB model [4] were based on a resource depletion model [15] that is even more conservative than the Conventional Resource case; higher uranium prices resulted in higher overall fuel cycle costs earlier than those found here. The introduction of a carbon tax and the resulting increase in nuclear energy demand also increases the rate of uranium resource depletion and the unit cost of uranium fuel.

3.2. Lower-Level Hierarchical Variations: Impacts of Internal Drivers

This section examines strategies and technologies for back-end material management. The resource and economic conditions necessary for the introduction of the commercial-power breeder reactors, however, are reported first.

3.2.1. Breeder Reactors

As described in Ref. [9], the cost of nuclear energy used to generate regional market shares is determined by means of an optimization procedure applied at each of the nine 15-year time intervals. This procedure compares a full range of LWR-breeder reactor mixes on a COE basis to determine the reactor makeup (LWRs and breeder reactors) for a given region and time that would minimize the overall cost of nuclear energy used to estimate market shares. For low uranium resource depletion (low costs), higher breeder capital and fuel-cycle costs, and without imposing added external costs for LWR-derivative plutonium and waste accumulations, addition of breeders to the nuclear energy mix generally increases the cost of nuclear energy [8]. For scenario attributes where breeder introduction reduces the overall cost of nuclear energy, the regional introduction of advanced breeder reactors is limited by a technology diffusion time [20].

A breeder reactor having a fifty percent higher direct cost relative to a LWR would not be economically competitive under the basis scenario demand (uranium cost scaling based on the Known Resource category). Within the model, three scenario attributes were modified to stimulate the introduction of breeder reactors:

a) use of the more conservative Conventional Resources uranium resource model;
b) reduce the capital cost of the breeder reactors in relationship to LWRs; and
c) stimulate overall demand for nuclear energy and demand for uranium by imposing carbon taxes or reducing overall costs of nuclear energy.

Time dependencies of economic- and technology-driven breeder introduction profiles on a range of favorable scenario attributes are illustrated in Fig. 7, where the fraction of all LWR-generated nuclear energy is determined under the assumption that all factors determining the time-dependence of the fraction of LWRs are independent of region. All cases examined used: a) the once-through LWR basis scenario; and b) scaled uranium cost according to the more conservative Conventional Resource scenario. The latter attribute is essential for breeder reactor introduction under realistic variations of the other scenario attributes listed above. With these assumptions, economic entry of the breeder occurs within the ~2100 time frame of this computation only for breeder cost increments (relative to LWRs) of ≤10 percent. Increasing the demand for nuclear energy (and uranium resources under the Conventional Resource scenario) by imposing a strong worldwide carbon tax both decreases the breeder introduction date and/or increases the cost threshold (Cases B and C, Fig. 7). Increasing the share fraction of nuclear energy by decreasing overall cost (Section 3.1.5.1) has a similar impact on breeder introduction, as does the imposition of a carbon tax, with both cases pertaining to breeder capital cost increments of 10 percent over that for LWRs. Finally, re-imposing the basis scenario resource attribute of Known Resource scaling, even with the conditions of low overall nuclear costs and a breeder cost increment of 10 percent (Case D), pushes breeder introduction to beyond the ~2100 time frame of this computation.

The main plutonium-inventory impact of scenario attributes that allows the economic introduction of breeders is the plutonium accumulated from previous LWR operations being transferred to the displacing breeder reactors. However, full global implementation of breeders under the Case D scenario is insufficient to meet new-reactor inventory demand. Increasing the breeding ratio from unity to 1.2-1.3 has little impact on the plutonium deficit; the demand by new breeders exceeds any breeding capacity on the time scales being considered.

3.2.2. Once-through LWRs

Except for the generation, flows, and inventories of nuclear materials, the once-through LWR scenario has been described essentially by the basis scenario. The majority of the plutonium for the basis scenario resides in spent-fuel form; inventories of separated (in reprocessing and MOX fuel fabrication) and fully recycled plutonium are nil. The breakout of the total plutonium inventory curve on a macroregional basis (OECD, REF, and DEV) is given in Fig. 8. Most notable from this figure is the shift in plutonium accumulations towards the developing regions, in spite of the large "head start" for the OECD countries. While the global distribution of total plutonium (mainly in spent-fuel form) appears to move towards global uniformity [8], plutonium contained in reactors initially becomes more uniform on a regional basis, but the large growth in developing regions skews the global distribution of reactor plutonium at later times.

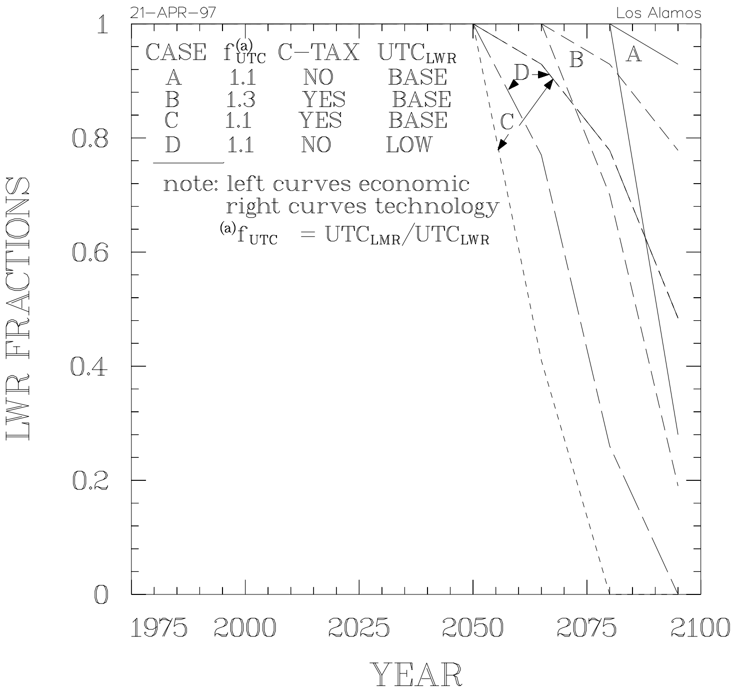

Figure 7. Time dependence of economics- and technology-driven introduction of LMRs on a range of favorable scenario attributes, where f_{LWR} is the fraction of all nuclear energy generated from LWRs under the assumption of a homogeneous world. The conservative Conventional Resource uranium resource [13] and associated costing scaling [8] was used for all four cases to enhance LMR introduction.

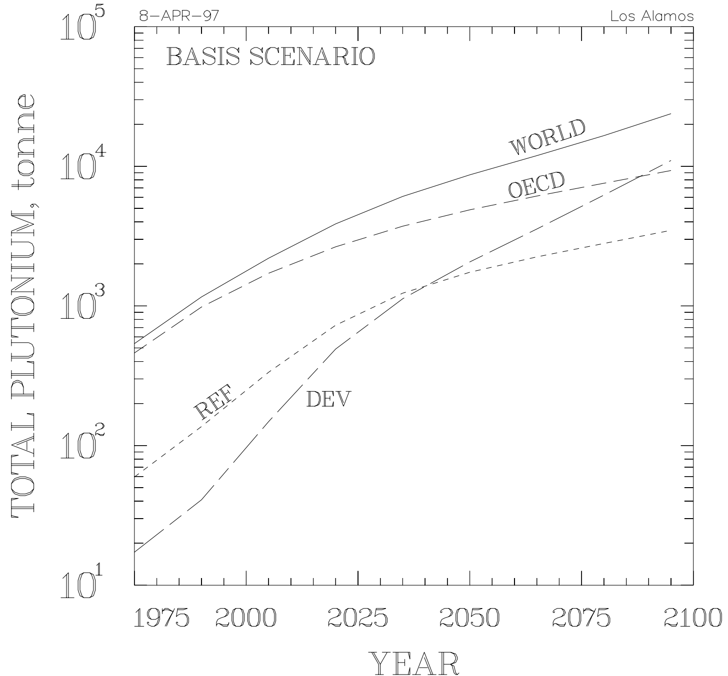

Figure 8. Macro-region breakout of total accumulated plutonium for the basis scenario (once-through LWRs, Known Resources [13]).

3.2.3. Plutonium Recycle in Light-Water Reactors

For each global region, the LWR recycle model forces the volume fraction of the core that is operated on MOX to follow a time dependent trajectory resulting in a globally averaged MOX fraction for all LWRs. The model does not make the choice of MOX fraction on economic grounds, nor does it constrain the introduction of MOX systems to account for possible regional deficiencies in plutonium supply that might arise. The function [8] used to drive the MOX fraction is characterized by the initial MOX core fraction, the final (asymptotic) MOX core fraction, the time at which the MOX trajectory is initiated, and a nominal doubling time used to determine the rate at which the MOX core fraction approaches the asymptotic value; all of these MOX characteristics are dependent on global region, although results reported herein pertain to a uniform world in this regard.

A present model limitation is the absence of an inter-regional plutonium allocation algorithm. For a given MOX fraction (uniformly applied to all global regions) and evolving demand for nuclear power, the amount of LWR- recyclable ($\leq$ 3 recycles) spent-fuel plutonium available in a particular region needed to supply new MOX fuel may fall below zero. For regions where such inventories are insufficient to meet local demand, a negative inventory is recorded that reflects plutonium being used in regional reactors that originated from outside that region. Presently, the tracking of regional total plutonium inventories includes only positive entries under the presumption that negative values of accumulated plutonium would be met from regions with surpluses through a set of allocation or ”market” rules. Whenever regional totals are presented, they reflect an inflation related to these unresolved “contributions” from regions with surpluses in order to resolve deficits in other regions. These deficits are resolved on a global basis, however, when total plutonium inventories are reported. In essence, regions that operate with negative inventories are allowed to push forward any market-driven growth in nuclear energy and increased use of MOX cores, but the required subtractions from regions with positive available plutonium inventories are made only at the global level. An alternative approach would limit the degree to which MOX is used in a given region to the regional inventories and/or production rates.

The evolution of the global plutonium inventories according to form is shown in Fig. 9 for a MOX core fraction of 0.3 (implementation begins in 2005 and is assumed to saturate at 0.3 around 2030). This figure indicates first a depletion in world values for available (LWR-recyclable) plutonium, followed by a recovery. Comparisons are given with the once-through and recycle (30 percent MOX core) cases reported in Ref. [7]. The buildup in plutonium that has been fully recycled and in separated (in reprocessing and MOX fuel fabrication) plutonium inventories is noted. The nominal basis LWR-based nuclear energy scenario coupled with choice of MOX fraction leads to a continued and growing inventory of multiple-recycled plutonium that is not usable in thermal LWRs. Until the impact of China becomes strong in the basis scenario (around 2040 - 2050), most of this multiple-recycled plutonium resides in OECD countries.

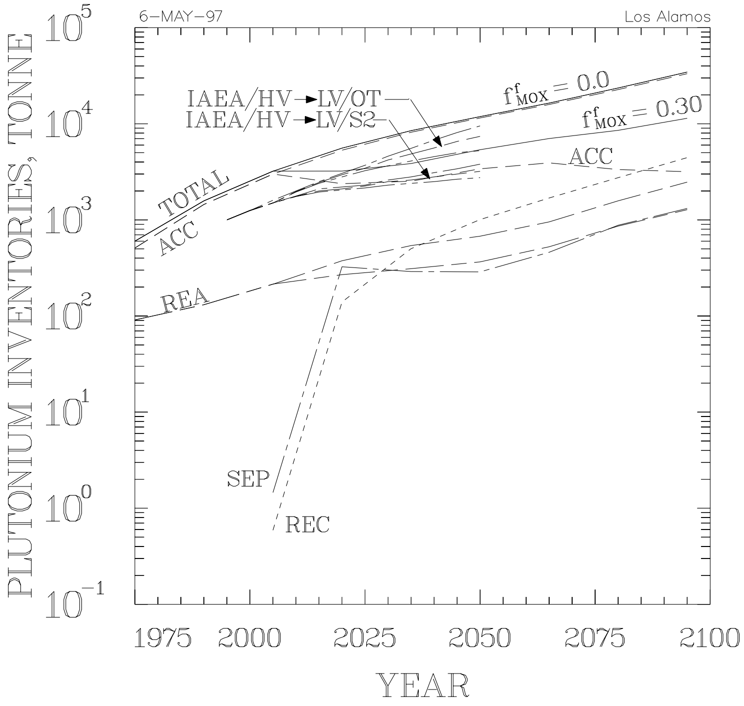

Figure 9. Time dependence of global plutonium inventories by form for a MOX core (volume) fraction of 0.30 beginning in ~ 2005 and taking 25 years to reach this asymptote. ACC = plutonium accumulated in spent fuel form that can undergo recycle back to the LWR; REC = plutonium that has experienced the maximum (N = 3) recycles; REA = average plutonium inventoried in reactors; SEP = separated plutonium in MOX fuel fabrication and chemical processing; TOTAL = ACC + REC + REA + SEP.

These results treat the world uniformly concerning level of plutonium recycling in each region. In reality, the trajectories occurring for plutonium recycle will depend on regional details, as determined by technical motivation and capability, economic status, and state of international controls/sanctions. Under some conditions [8] (*e.g.*, higher MOX core volume fractions, higher burnups, higher plutonium loaded into MOX, *etc.*), a moderate imbalance can a result in the world accumulated (ACC) inventories becoming slightly negative for short periods. Temporal and regional tailoring of the MOX fractions can flatten global accumulations of LWR-recyclable plutonium close to zero, which in ideal circumstances would be the role of the "market." Finally, the long-term impact of plutonium use in LWRs on the uranium resource and cost is moderate for the basis scenario, generally being in the range of 25 percent for a MOX core fraction of 30 percent around the year 2075. Furthermore, the increased cost of reprocessing and MOX-fuel fabrication for the basis scenario increases cost somewhat, which translates approximately into a 10 per cent reduction in global demand in 2050 [8].

3.2.4 Fast-Spectrum Plutonium Burners

The use of fast-spectrum burners (FSBs) (see Ref. [21] for recent design studies) to fission more completely all isotopes of plutonium and the minor actinides (*e.g.*, neptunium, americium, and curium) is examined here. The results of Section 3.2.1. indicated that little or no penetration of breeder reactors (on economic and resource-availability grounds) might be expected until the late 21st century, or beyond. However, FSB systems might be used in conjunction with LWRs (operating under either once-through or multiple-recycle conditions) to create alternative approaches for dealing with the plutonium inventories accumulating from LWRs. The use of FSBs, like the LMR/IFR [21, 22] or accelerator-based (ATW) [23, 24] systems, is expected to incur some economic penalty, in that these systems may have capital and operating costs that would require the sale of electrical power at higher COEs than from LWRs that accumulate plutonium at low to moderate charges. In conducting a preliminary inquiry into potential roles of FSBs, the following preliminary questions were addressed:

a) To what extent must the COE be incremented for a LWR-based economy that is supported by some fraction of FSBs?
b) What is the impact on regional and world nuclear energy demand if the FSB route to dealing with LWR-generated plutonium is taken?
c) To what extent and on what time scale are accumulated plutonium inventories diminished by specific FSB approaches, and to what extent are plutonium inventories actually destroyed *versus* merely shifted (*e.g.*, from accumulated LWR spent fuel to active FSB inventories, including integral processing)?
d) Do significant top-level differences exist for ATW *versus* LMR approaches to plutonium management via FSBs?

While generally efficient in terms of the fraction of total thermal power that is delivered for sale on the electrical grid, the LMR requires non-zero plutonium conversion ratios [21] for reasons of neutronic stability. This constraint results in a non-zero internal “circulation” of plutonium and a corresponding diminution of capacity to serve LWR clients.

The accelerator-based (ATW) approach to FSBs has no intrinsic, safety-driven need to “recirculate” plutonium, but the ATW has a higher recirculating power requirement and a higher capital cost; both of these requirements reflect burdens associated with the accelerator needed to drive a subcritical target/blanket system. High intrinsic plutonium inventories are associated with the LMR (and possibly ATW), however.

To begin addressing these questions, a simplified model [8] was implemented into the ERB model wherein the factor by which the cost of LWR-based nuclear energy would be increased was used to reflect the economic penalty associated with a particular FSB scheme back to the market-share determination. This factor is a function of the support ratio of FSBs to LWRs based on the fraction of the total nuclear capacity provided by the FSBs in a given global region at a given time. The support ratio is controlled by an exogenously specified prescription that gives the rate at which accumulated plutonium can/should be reduced. Additionally, the (maximum) magnitude and deployment rate of FSB capacity is constrained [8].

The FSB results presented here are limited to departures from the once-through LWR basis scenario. More comprehensive analysis of optimal ways to manage civilian plutonium must balance: a) the “real” (and presently undetermined) cost of direct disposal of LWR spent fuel; and b) the costs of LWR recycle as a front-end burner compared to more expensive FSB systems having as a main attribute the ability to deal with plutonium forms that cannot be efficiently fissioned in LWRs.

Only regional scenarios for FSB deployment have been considered. Supra-regional implementation and greater cost sharing may present a more economic approach that remains to be examined. Generally, the results of the constrained deployment algorithm [8] for any given region depend on the growth of nuclear power and plutonium inventories in that region, and on the magnitude of the constraints imposed on FSB deployment rates and magnitudes (relative to LWR capacity). Regions with a longer history of nuclear power and accumulated plutonium begin at the constrained FSB capacity, and, depending on subsequent growths in nuclear energy, fall below that limit later in the 21st century. The reformed economy (REF) regions are intermediate in reaching that limit, and the developing (DEV) regions do not come close to reaching the FSB capacity limit imposed.

For the LWR *versus* LMR financial and costing parameters used [a minimum capital cost penalty of 50 percent for FSBs and somewhat higher fixed charge rates (higher risk) and operating and maintenance charges], the cost impact is significant (~30%) for "heavy users" during the early deployment of LMR-based FSBs (when the demand is high and the support ratio is at the constrained lower value). Later in time, when LWR-accumulated plutonium has diminished (*e.g.*, either fissioned or deployed in the high-inventory FSBs), the cost impact approaches the 10-15% level.

The nuclear energy costs passed back to determine market shares have been increased for each region at each time by the COE-increment factor described above. The impact of these increased costs on global nuclear energy demand is shown in Fig. 10, where three FSB scenarios are compared with the basis scenario, as well as the IAEA high/medium/low-demand scenarios [7]. The three FSB scenarios are: LMR with plutonium conversion ratios of 0.6 and 0.2, and ATW with a zero conversion ratio, reduced intrinsic plutonium inventory, reduced engineering gain, and increased unit total cost (~17 percent more than the LMR [8]). The impact of reducing the capital cost of LMRs relative to LWRs from 1.5 to 1.1 is also shown in Fig. 10. Within the uncertainty of this highly aggregated costing model, the LMR/FSB and the ATW/FSB appear to trade the economics of internally circulated plutonium for internally circulated power to give nominally the same (low) support ratio and elevated values of cost of electricity.

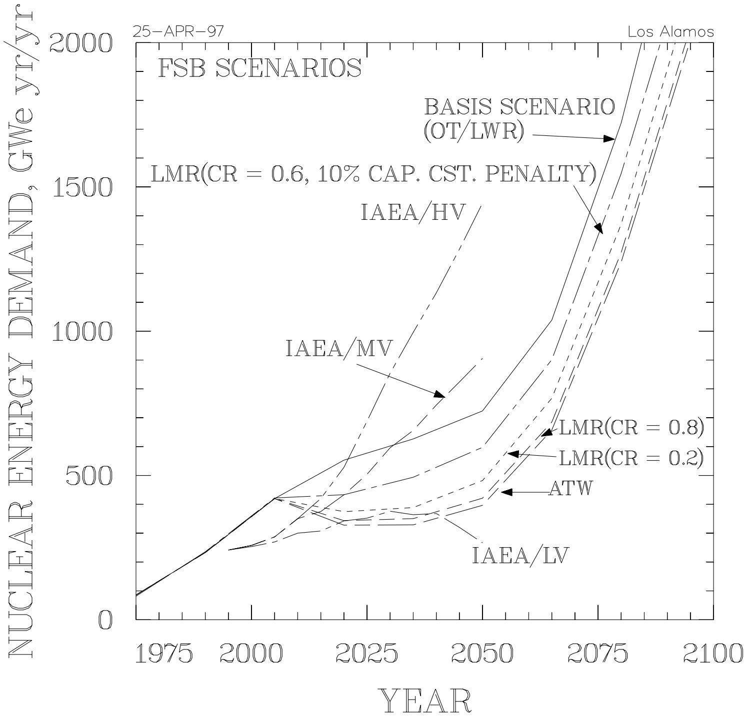

Figure 10. Impact of FSB implementation on nuclear energy demand for three scenarios [LMR(CR = 0.6); LMR(CR = 0.2), where CR is the conversion ratio; and ATW] as determined by the COE increases associated with more expensive FSBs operated synergistically with once-through LWRs; comparisons are made with the basis scenario and the Ref. [7] demand variants. The case with a lower cost penalty (FSB penalty reduced to within 10 percent of LWR costs) is shown for a LMR with CR = 0.6.

The temporal and regional impacts on LWR-accumulated plutonium inventories for the 0.6 conversion ratio LMR and the moderate recirculating power ATW scenarios are reported in Ref. [8]. For all cases, the constrained limit on FSB deployment rate was encountered for all regions at all times. The constrained implementation rate was found to be insufficient to restrain the growth of accumulated plutonium in the China region in later periods. While the decreases in LWR-accumulated plutonium are significant, a large part of this plutonium is used to start up the high-inventory FSBs. Fully recycled and separated plutonium forms do not appear for this once-through LWR case, since the FSBs being considered invoke integral processing. Lastly, it should be noted that the comparison between the basis scenario and the FSB scenario must accommodate differences in demand for nuclear energy brought about by the expense of the adopted FSB schemes.

4. SUMMARY AND CONCLUSIONS

A range of long-term futures for nuclear energy has been examined by building relatively "surprise-free" scenarios using a consistent, but simplified, modeling tool. By varying a wide range of upper-level scenario attributes (external forces), a spectrum of remarkably similar nuclear energy demand scenarios can be generated. Although these scenarios represent only possibilities, they nevertheless provide a quantitative basis and connectivity for examining impacts of the lower-level attributes (internal drivers) that influence directly the economic and operational character of nuclear power. Furthermore, although these analyses are "surprise free," the impacts of unexpected future events could possibly be interpreted if translation of the latter into terms that reflect upper-level hierarchical variations can be made.

Synoptic interim conclusions derived from each level of this analysis include:

a) Upper-Level Hierarchical Variations: Nearly identical high, medium, and low nuclear energy variants [7] can be generated from a wide range of external drivers. A general, consistent trend indicates continuation of the present demographics of nuclear energy (operation mainly in OECD countries) followed by a transition to developing nations dominance (particularly China) for times beyond 2050. Strong carbon taxation both reduces GHG emissions and widens the economic niche of nuclear energy, while moderately decreasing overall primary energy demand and GNP. Lowered nuclear cost (and increased nuclear share) by itself does not produce similar GHG impacts, indicating a need to explore non-electric applications of nuclear energy in competition with other sources of sustainable energy.

b) Lower-Level Hierarchical Variations: Interim conclusions for the three lower-level scenarios examined include:
   - Once-Through or MOX-Recycle in LWRs: With growth in nuclear energy, so grows plutonium inventories. Depending on regional and temporal details of this scenario and the local demand generated for given upper-level scenario attributes, the places where this plutonium resides (in reactor, processing, spent fuel, *etc.*) will shift over time and region. Trends for the next 50 years follow those for demand scenarios in that the majority of plutonium will reside in industrialized states with a shift towards developing nations occurring later in the 21st century.
   - Economically Competitive Breeders: Based solely on economic considerations, breeder reactors appear in the marketplace only if: a) conservative uranium-resource assumptions are invoked (CR resource scaling); b) relatively low capital costs are possible (Û 10 percent that of LWRs); and/or c) significant costs for fossil fuel arise beyond the resource-depletion algorithms used in the ERB model (*e.g.*, strong carbon taxes globally applied, Fig. 5).
   - Fast-Spectrum Burners: For the parameters used, systems based either on LMRs or accelerators, even when limited in (minimum) support ratio and deployment rate, can have significant impacts on nuclear energy cost and the demand that results. If the LMR requires a minimum conversion ratio (~0.6), this approach to dealing with the LWR-accumulating plutonium results in unattractive support ratios that increase the cost of the LWR-FSB synergy and decrease demand. The ATW offers an advantage in support ratio, but operation with a moderately multiplying blanket increases the recirculating power relative to the LMR, again increasing cost and reducing demand for the LWR-FSB synergy.

Closing the nuclear fuel cycle in the broadest and long-term context means stemming growing quantities of plutonium while stably isolating hazardous fission product waste for times required to achieve benignity. The separation of plutonium from fission products followed by inventory reduction through recycle and fissioning can, under optimal conditions, extend resources, reduce proliferation risk, and conserve repository capacity. Economic penalties, however, will be incurred, but the impact of these penalties on overall demand for nuclear energy must be assessed in terms of the variability of the external drivers that establish the base demand scenario(s). The interim results presented herein point to directions where this desirable goal may reside, but considerably more real technical progress is needed before this desirable situation becomes a reality.

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