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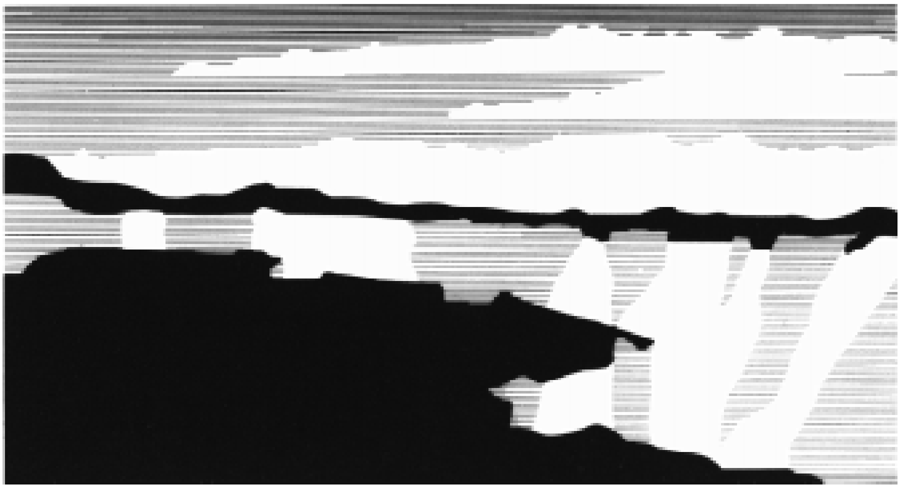

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ABSTRACT

A global energy, economics, and environmental (E^3) model has been adopted and modified with a simplified, but comprehensive and multi-regional, nuclear energy module. Using this model, consistent nuclear energy scenarios are constructed. 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. Impacts of a range of nuclear fuel-cycle scenarios are reflected back to the higher-level scenario attributes. An emphasis is placed on nuclear materials inventories (in magnitude, location, and form) and their contribution to the long-term sustainability of nuclear energy and the future competitiveness of both conventional and advanced nuclear reactors.

I. INTRODUCTION

The goal of this study is to advance understanding of regional and long-term impacts of nuclear fuel-cycle strategies on regional and global market shares assumed by nuclear energy. 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] wherein 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. The attributes that describe 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, inter-regional migrations, *etc*.). Most of the attributes of the nuclear energy scenarios examined in this study fall into the lower hierarchical echelons, which include in descending order policy, market, and technology.[3] The framework to examine key scenario impacts uses a global E^3 model[4] that has been modified to include material-inventory, economic, and nuclear-proliferation characteristics unique to nuclear energy.[5,6]

This study addresses the following two generic questions concerning the future of 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 (*e.g.*, once-through LWRs, plutonium recycle in thermal-spectrum reactors, advanced fast-spectrum plutonium burners)?

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

II. APPROACH

This section summarizes the model and a "basis scenario" used as a point-of-departure for sensitivity studies. An elaboration of this work is given in Refs. 3 and 7.

A. Model

Scenarios can be classified as both "descriptive" and/or "normative".[8] A "descriptive" scenario evolves *via* a rule-based model without significant geopolitical, policy/institutional, economic/market, or technology changes, whereas a "normative" scenario allows for interactive modifications of these respective areas. Studies by the World Energy Council (WEC)[9] and by a cooperative effort between the International Institute for Applied Systems Analysis (IIASA) and the WEC[8] are recent examples of scenario characterization of long-term, global energy systems. A recasting of the procedure used to generate scenario attributes into a hierarchical format lends a needed separability of key drivers of future scenarios while providing both a focus and an intercomparability to related studies. Five hierarchical levels for scenario rule/definition-making, as elaborated in Ref. 3, are implemented in the use of the global E^3 model.

The ERB (Edmonds, Reilly, Barns) model[4] 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 intervals) times covering the period from 1975 to 2095. The demand for energy services in each global region is determined by: a) the cost of providing these services; b) level of income (~GNP); and c) regional population and top-level demographics.

The nuclear model developed and operated "under" the ERB model[6] performs three primary functions: a) 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) tracks the flow of key nuclear materials throughout the nuclear fuel cycle (natural uranium, low-enriched uranium, plutonium, and spent fuel) for use in subsequent nuclear materials and proliferation-risk assessments; c) performs a multi-attribute utility analysis of proliferation risk associated with the civilian fuel cycle.[10]

The uranium resource description originally used in ERB model,[4] for purposes of the present study, has been replaced with that of Ref. 10. The nuclear model is based on the uranium/plutonium cycle, as utilized by an economically determined mix of light water reactors (LWR) and breeder reactor systems. 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[6] that accounts for annual capital charges, annual plant operating and maintenance charges, and annual charges related directly to the nuclear fuel cycle. For each global region and time interval, the COE-minimizing fraction of nuclear energy delivered by LWRs (for a given exogeneously determined MOX recycle core 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.

The nuclear fuel cycle is described in terms of the usual sequence of processes.[12,13] The simplified species-resolved mass balances, based on input-output analysis,[12] are used to model regional and temporal nuclear material flows. Plutonium flows and accumulations are monitored for each global region as a function of time, with reactor plutonium (REA), separated plutonium in reprocessing and fuel fabrication (SEP), and accumulated plutonium in spent fuel [differentiated into LWR-recyclable (ACC) or non-recyclable forms (REC)] being the four major categories tracked.

B. Basis Scenario

The "basis scenario" provides a point-of-departure to which shifts driven by upper-level or lower-level hierarchical variations can be referenced. 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. 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 of scenario attributes.[3]

The top-level scenario attributes that characterize the basis scenario use the data base (with some modification) generated for an application of the ERB model to understanding the economics of carbon-dioxide emission control,[4,14] with modifications and upgrades related to the present study being summarized elsewhere.[3,7] The basis scenario that results is shown on Fig. 1. The 13 global regions have been aggregated into three global macro-regions: industrialized countries [OECD: US, Canada, Western Europe (OECD-Europe), Japan/Australia/South Korea (OECD-Pacific)]; reforming economies [REF: Eastern Europe (EEU), Former Soviet Union (FSU)]; and developing countries [DEV: China, Southeast Asia (SEA), India (IND), Latin America (LA), Northern (NAFR) and Southern Africa (SAFR), Middle East (ME)]. Comparisons of total primary energy and total nuclear energy projections with WEC results[8,9] *via* the IAEA study[15] are reported in Figs. 1. Aggregated growth rates of GNP, primary energy, and energy intensity also compare favorably.[3]

III RESULTS

The results are divided into two broad categories: external drivers (*i.e.*, variations in upper-level parts of the scenario attribute hierarchy, *e.g.*, "predetermined conditions"[1]); and internal drivers (*i.e.*, variations in attributes that reside at the lower rungs of that hierarchy). Departures from the basis scenario nuclear energy demand are caused by changes in these upper-level attributes. The impacts of drivers that are internal to nuclear energy 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.

A. Upper-Level Hierarchical Variations: Impacts of External Drivers

The five external drivers (population, GNP, energy intensity, taxes, and "top level" nuclear economics) define the main "external drivers". All upper-hierarchical variations are single-point perturbations about the basis scenario, which is characterized by a once-through LWR fuel cycle, a uranium resource classified by Known Resources (KR),[11] no carbon taxes, and breeder reactors that are 50% more expensive than LWRs on a unit total cost [UTC ($/We)] basis.

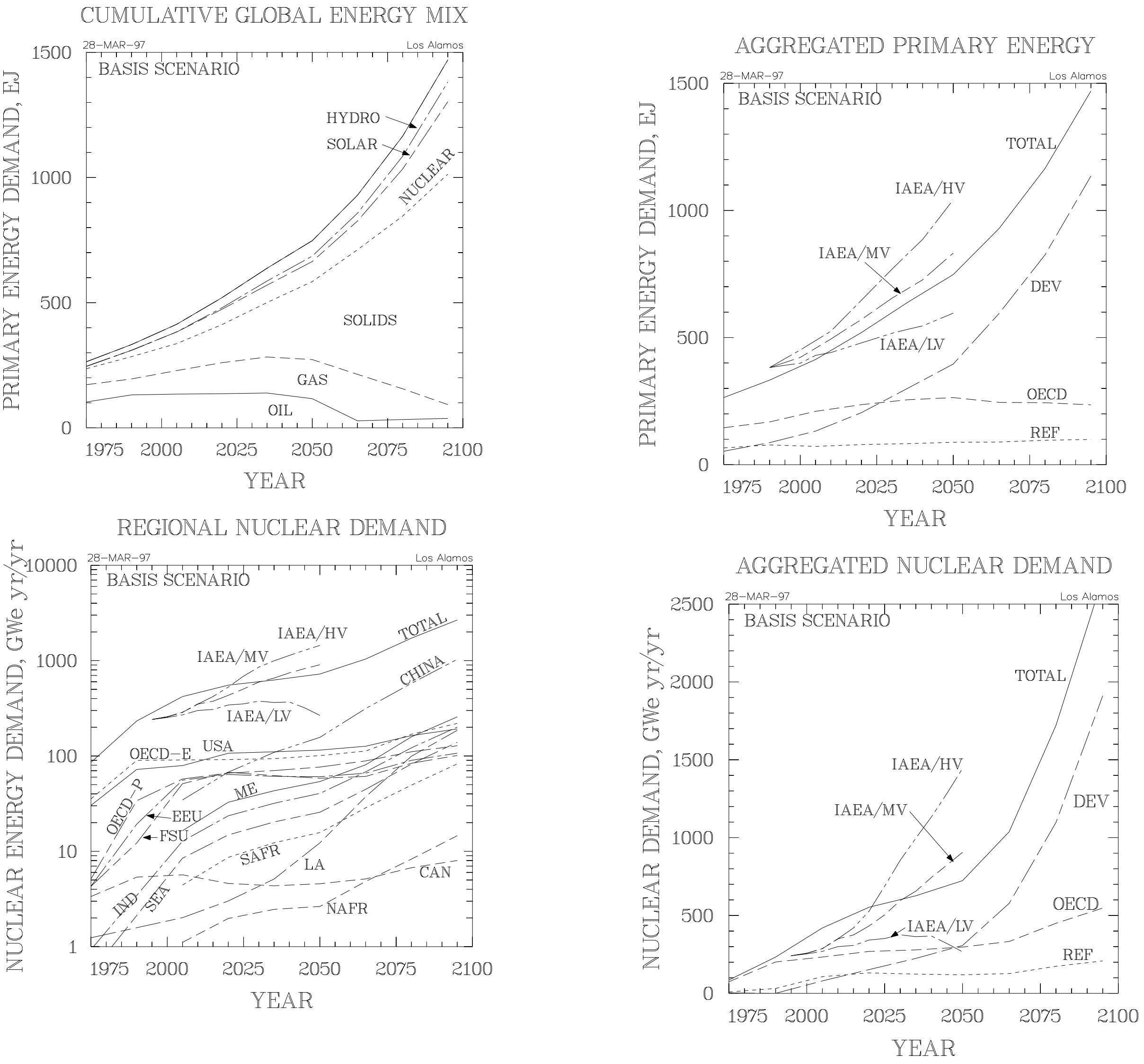

Figure 1. Evolution of total primary and nuclear energy for the basis scenario; a comparison is made with the Ref. 15 high (HV), medium (MV), and low (LV) variants, as adopted from the WEC/IIASA[8] study. (refer to text for definitions)

1. Population

The basis scenario and most of the related departure scenarios follow the U.N. population projection of nearly 12 billion persons on earth by the year 2100. Adjusting[3] 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. Typically, the proportional change in nuclear energy demand tracks the population changes.[3]

2. Workforce Productivity

The ERB model adjusts a base regional GNP in time for: a) population increase; b) an aggregated price for energy services using region-dependent price elasticities; and c) an increase in workforce productivity, which is expressed as a region- and time-dependent rate of annual productivity enhancement.[4] The impact of region-independent increases and decreases in productivity by ~±20% on GNP was examined.[3] 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, for the income elasticities used in the ERB model, are highly nonlinear compared to the single-point population variations alone; a 20% decrease in productivity over the period out to ~2100 reduces the demand for nuclear energy by $\lesssim$ 50% relative to the basis scenario, as is shown by the collection of results given in Fig. 2. The impact of these scenario attributes on the fraction of total primary energy provided by nuclear is summarized on Fig. 3.

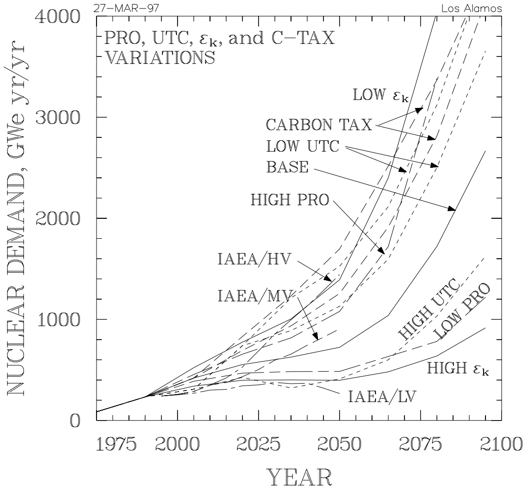

Figure 2. Impact of productivity (PRO), energy-efficiency (ε_k), capital-cost (UTC), and carbon-tax (C-TAX) variations on nuclear energy demand; comparison with Ref. 15 scenarios is given.

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. Generally, a decrease in the primary-to-secondary energy conversion efficiency *versus* time[3] results from regional populations demanding higher forms of energy (liquids and electricity) to meet the energy service demands of a growing population that experiences increased wealth. The impacts of a range of technology improvement rates on nuclear energy demand and share fraction are also shown in Figs. 2 and 3.

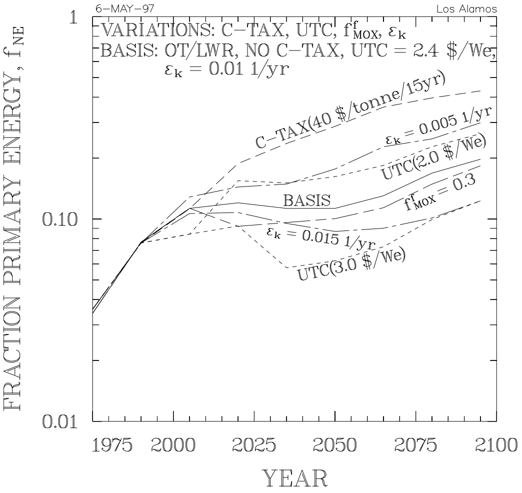

Figure 3. Impact of key scenario attributes on nuclear energy share fraction of total primary energy demand.

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), while increasing the market share for reduced- or zero-carbon energy sources. The impact of applying a moderate (20 \$/tonne/15 yr) and strong carbon tax rate (40 \$/tonneC/15yr) on the demand for nuclear energy is shown on Fig. 4. The higher carbon tax rate stabilizes total carbon emission to values associated with the year of implementation. Halving this tax 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 results 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.[14]

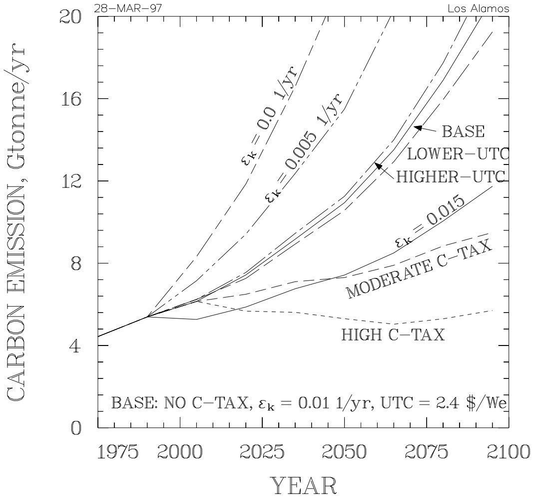

Figure 4. Impact of energy-efficiency (ε_k), capital-cost (UTC), and carbon-tax (C-TAX) variations on atmospheric carbon emissions.

B. 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 commercial-power breeder reactors are also reported.

1. Nuclear Economics

For the basis scenario conditions (*i.e.*, uranium resource = KR, breeder reactors 50% more expensive than LWRs), the breeder reactor is not competitive within the time frame of this computation.

a. Capital Cost. For the uranium resource model used and the unit costs associated with the once-through LWR fuel cycle,[3] 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 isembodied in a single variable - the unit total cost, UTC($/We). The basis scenario adjusted this cost in 1975 and 1990 for relevant regions so that the model returns an annual nuclear energy generation that approximates 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 asymptote to 3.0 or 2.0 $/We, respectively, are shown in Figs. 2 and 3. All regions were treated equally for times greater than 2005. As is indicated on Fig. 4, the impact of these unit cost variations on atmospheric carbon emissions is small compared to the imposition of carbon taxes. Generally, carbon taxation creates a favorable environment for nuclear energy growth with reductions in carbon emissions, but the cost-driven increase or decrease in nuclear energy demand alone have little impact on atmospheric carbon emissions.

b. Uranium Resource. The basis scenario assumes that the Known Resources (KR) category[10] describes reality. The weight fraction of ^{235}U in tailings is determined by the minimum-cost conditions[12,13] for the relative values of mined/milled uranium unit cost and a chosen unit cost of enrichment[3] (~100 $/SWU). A minimum price of 100 $/kgU for mined/milled uranium is enforced for all resource categories.

The dependence of uranium usage, unit cost, and optimal enrichment on time and uranium resource assumption is described in Ref. 3. For both Known Resource and the Total Resource (TR) categories,[11] uranium costs remain at the threshold price for the basis scenario nuclear energy demand, although a departure from the threshold price beyond ~ 2080 occurs for the basis scenario. The Conventional Resource (CR) 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. 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; with increasing uranium costs and decreased capital costs, however, breeder reactors can become economic (relative to LWRs) before 2100.

2. Breeder Reactors

The cost and mix of nuclear energy used to generate regional market shares is determined by means of an optimization procedure applied at each of the nine times (15-year intervals). For low uranium resource depletion (low costs), higher breeder capital (50% more than LWRs) 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 increases the overall cost of nuclear energy. Three scenario attributes were modified to stimulate the introduction of breeder reactors: a) use of the more conservative CR uranium resource category; 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 by reducing overall costs of nuclear energy.

Time dependencies of economic- and technology-driven[16] breeder introduction profiles on a range of favorable scenario attributes are illustrated in Fig. 5, where the fraction of 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 CR 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 only for breeder cost increments (relative to LWRs) of ≤10%. Increasing the demand for nuclear energy (and uranium resources under the CR 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. 5). Increasing the share fraction of nuclear energy by decreasing overall cost 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% over that for LWRs. Finally, re-imposing the basis scenario KR uranium resource attribute, the conditions of low overall nuclear costs, and a breeder cost increment of 10% (Case D) pushes breeder introduction to beyond the ~2100 time frame.

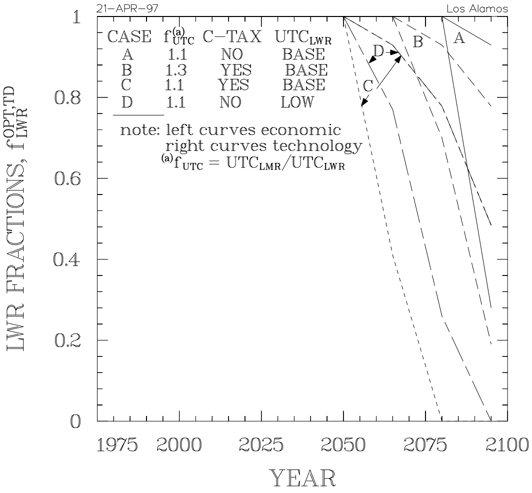

Figure 5. Time dependence of economics- and technology-driven[16] introduction of breeder reactors on a range of favorable scenario attributes.

3. Once-through LWRs

The once-through LWR scenario is described 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. A breakout of the total plutonium inventory curve on a regional basis is given in Fig. 6. 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,[3] plutonium contained in reactors initially becomes more uniform on a regional basis; the large growth in developing regions, however, skews the global distribution (of reactor plutonium) at later times.

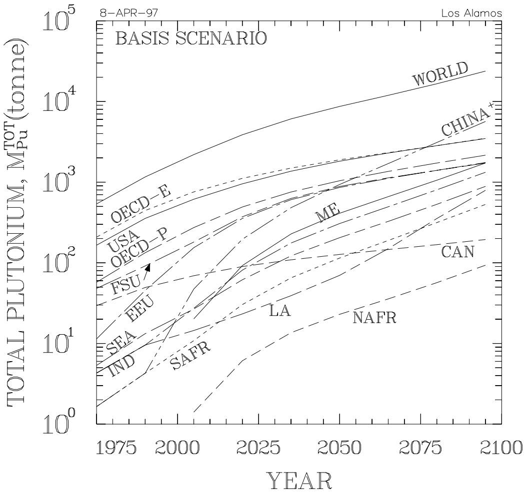

Figure 6. Regional breakout of total plutonium inventories for the basis scenario.

4. Plutonium Recycle in LWRs

For each global region, the LWR recycle model forces the MOX core volume fraction to follow a time-dependent trajectory. 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. For regions where inventories are insufficient to meet local demand, a negative inventory is recorded that reflects plutonium being used in regional reactors that originated from other regions. Regional totals presented herein reflect an inflation related to these unresolved balances. Deficits are resolved on a global basis, however, when total plutonium inventories are reported.

The evolution of the global plutonium inventories according to form is shown in Fig. 7 for a (globally averaged, asymptotic) MOX core fraction of $f_{\mathrm{MOX}}^{f} = 0.3$ (implementation begins slowly in 1990, rises steeply in 2005, and saturates at f_{MOX}^{f} around 2030). This figure indicates first a depletion in world inventories of available (ACC, *i.e.*, LWR-recyclable) plutonium, followed by a recovery, and then a further depletion.

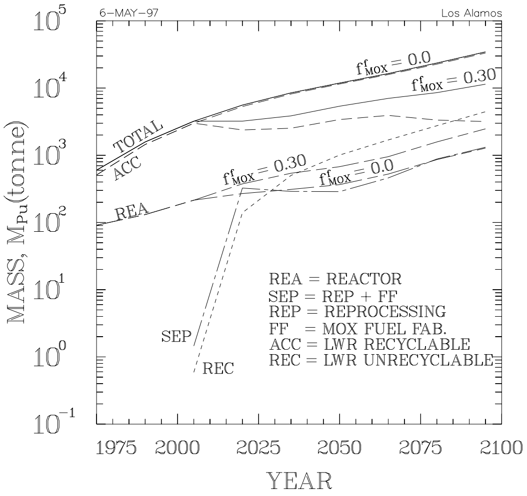

Figure 7. Time dependence of global plutonium inventories by form for a globally averaged MOX core fraction of 0.30.

Comparisons are given in Fig. 7 with the (once-through LWR) basis scenario. The buildup in plutonium that has been fully recycled (REC) and in separated (SEP) plutonium inventories is noted. Until the impact of China becomes strong in the basis scenario (around 2040 - 2050), most of the multiple-recycled plutonium resides in OECD countries. The long-term impact of plutonium recycle in LWRs on the uranium resource and cost is moderate for the basis scenario, and is generally in the range of 25% for $f_{\mathrm{MOX}}^{f} = 0.3$ around the year 2075. Furthermore, the increased cost of reprocessing and MOX-fuel fabrication for the basis scenario increases overall COE somewhat; this increase translates into ~10% reduction in global demand in 2050.[3]

5. Fast-Spectrum Plutonium Burners

The use of fast-spectrum burners (FSBs)[17,18] to fission more completely all isotopes of plutonium and the minor actinides has been explored here. The results of Sec. III.B.2. indicated little or no penetration of breeder reactors (on economic and resource availability grounds) until well into the latter half of the 21st century, if not 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[17,18] or accelerator-based (ATW)[19,20] systems, is expected to be accompanied by some economic penalty and decreased demand, however.

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[17] 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 FSB has no intrinsic, safety-related need to "recirculate" plutonium, but the ATW is expected to have a higher recirculating power requirement and a higher (than LMR/IFR) capital cost;[19] 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[3] was implemented in 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 exogenous prescription that specifies the rate at which accumulated plutonium can/should be reduced, as well as the (maximum) magnitude and deployment rate of FSB capacity.

The FSB results presented here are limited to departures from the 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 burned in LWRs. Also, only regional scenarios for FSB deployment have been considered; supra-regional implementation and greater cost sharing may present a more economic approach.

For the LWR *versus* LMR financial and costing parameters used [a minimum capital cost penalty of 50% for FSBs and somewhat higher fixed charge rates (i.e., 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 burned or deployed in the high-inventory FSBs), the cost (COE) impact approaches the 10-15% level. The reflection of these increased costs on global nuclear energy demand is shown in Fig. 8, where three FSB scenarios are compared with the basis scenario: 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 % more than the LMR).[3] The impact of reducing the capital cost (UTC) of LMRs relative to LWRs from 1.5 to 1.1 is also shown in Fig. 8. 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 COE.

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. 3. For all cases, the constrained limit on FSB deployment rate was encountered for all regions at all times.[3]

The constrained implementation rate was found to be insufficient to hold down the growth of accumulated plutonium in China at later times. 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, and as such appear in reactor inventories.

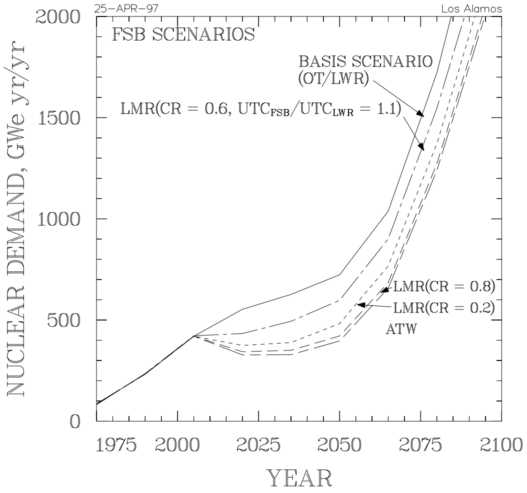

Figure 8. Impact of FSB implementation on nuclear energy demand for three scenarios.

IV. 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 (*i.e.*, external forces), a spectrum of remarkably similar nuclear energy demand scenarios result. Although these scenarios represent only possibilities, they nevertheless provide a quantitative basis and connectivity for examining impacts of the lower-level attributes (*i.e.*, 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 possibly could be interpreted if translation of the latter into terms that reflect upper-level hierarchical variations can be made.

Interim conclusions derived from each level of this analysis include:

- General:

  A range of remarkably similar nuclear energy demand scenarios can be generated by varying a wide range of upper-level scenario attributes (external drivers or "predetermined conditions"[1]). The connectivity between these "external drivers" and drivers that are "internal" to nuclear energy requires further study.

- Upper-level (external driver) scenario attributes:
  - "demographics" of nuclear power for the basis scenario shift from OECD regions to the DEV regions after ~2050;
  - modest (single-point) variations in both population and productivity have important impacts on high-*versus*-low nuclear energy demand scenarios, with greater than linear responses occurring for the latter;
  - strong carbon taxation rates (40 $/tonneC/15yr) broadens the economic niche for nuclear energy, while stabilizing atmospheric carbon emissions;
  - decreased capital cost for nuclear (electric) power increases market shares, but with little impact on atmospheric carbon emissions;
  - stalled progress in reducing energy intensity increases nuclear energy market share, but carbon emissions dramatically increase above the already high basis scenario levels.

- Low-level (internal driver) scenario attributes:
  - once-through LWRs: while plutonium accumulates at the nominal rate of ~190-230 kgPu/GWe(capacity)/yr, a strong OECD → DEV shift in nuclear energy use and plutonium accumulations occurs after ~2050 for the basis scenario;

– MOX-recycle in LWRs: while (globally uniform) MOX recycle can reduce total plutonium inventories by ~2-3, important shifts in form occur (REA, SEP, and REC increases; ACC decreases); unrestrained MOX implementation (to ~30% average core fractions) requires strong inter-regional transport to meet local deficits; the level of plutonium destruction and rendering to LWR-unusable form depends sensitively on number of recycles, burnup, and plutonium loadings;

– Breeder reactors: competition with LWRs occurs only for the CR uranium resource[11]; capital costs within ~10% of LWRs; and/or increased fossil-fuel prices (*e.g.*, strong carbon taxation rates) for the basis scenario;

– Fast Spectrum Burners: LWR/FSB synergies having acceptable economic (demand) impact for nuclear energy require high support ratios (*e.g.*, reduced plutonium "recirculation" for LMR/IFR), reduced financial and operating risks (*e.g.*, decreased fixed-charge rates), reduced capital costs (relative to LWRs), and/or reduced recirculating power (for ATWs); at the present level of analysis, ATWs *versus* LMR/IFR trade off the above-listed elements, with both having a strong negative economic impact for the parameters chosen.

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 burning 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 desirable scenarios can be transformed into reality.

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