

Analyzing the Reprocessing Decision: Plutonium Recycle and Nuclear Proliferation

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Analyzing the Reprocessing Decision: Plutonium Recycle and Nuclear Proliferation

NP-931
Research Project 620-24

Final Report, November 1978

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

This final report, Analyzing the Reprocessing Decision, presents the conclusions and detailed support calculations of an EPRI-sponsored doctoral dissertation conducted at the Mechanical Engineering Department of Stanford University. It represents a state-of-the-art treatment of one of the more important nuclear policy questions facing decision makers. As such, it extends earlier treatments of the topic. At the same time, it should be realized that the numerical values are based on the author's estimates of key parameters and not those of EPRI. The project was funded through the Systems and Materials Department of EPRI's Nuclear Power Division as part of a series of ongoing studies that examine important problems related to the nuclear fuel cycle. These studies address not only the technical and economic aspects of reprocessing, nuclear waste disposal, and other back-end operations, but also the impact of fuel-cycle technology on risks to public health and safety and on risk of nuclear proliferation. Placing these risks in perspective with the economic incentives for fuel-cycle development is a major objective of these studies.

PROJECT OBJECTIVES

Recent studies of the cost-risk benefits of reprocessing have neglected to quantify the risk-related costs or include the effects of uncertainty in their economic calculations. Critics of nuclear power and reprocessing assert that the proper consideration of hidden costs and uncertainty would tip the balance away from the nuclear option. This project establishes a methodological framework in which both costs due to risks and economic uncertainties are explicitly incorporated. Costs that arise from three categories of technological risk were quantified and compared for decision options. These included risks related to public

health, the environment, and safety; nuclear theft and sabotage (safeguard risks); and nuclear proliferation. Particular attention was focused on treating proliferation risk quantitatively, since previous studies have not treated the problem from such a perspective.

CONCLUSIONS AND RECOMMENDATIONS

The study concludes that reprocessing and plutonium recycle should be permitted to proceed as planned in the United States, since the economic benefits of so doing greatly outweigh the risk-related costs. The quantification of benefits is noteworthy because it includes a category of breeder-related benefits resulting from the recognition that reprocessing must be commercialized prior to the introduction of a plutonium-based breeder reactor (e.g., the LMFBR). Reprocessing delays in this model result in LMFBR delays and consequent reductions in benefits to society. The structure of the analysis in this report correctly emphasizes the factors that must be modeled and quantified if the societal factors affecting the reprocessing decision are to be incorporated into the policy maker's cost-benefit equation.

Robert F. Williams, Project Manager
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ABSTRACT

The United States decision to defer indefinitely the reprocessing of spent nuclear fuel is examined in this thesis. Bayesian decision analysis is applied to develop a rational framework for the assessment of alternatives. Benefits and costs for each alternative are evaluated and compared in dollar terms to determine the optimal decision. A fuel cycle simulation model is constructed to assess the economic value of reprocessing light water reactor (LWR) spent fuel and recycling plutonium. In addition, a dynamic fuel substitution model is used to estimate the economic effects of the reprocessing decision's influence on the introduction date of the liquid metal fast breeder reactor (LMFBR). The analysis of benefits and costs is extended to include the social costs due to technological risks, such as accident risk, nuclear theft and/or sabotage, and international nuclear proliferation. These social costs are expressed in dollar terms for comparison with the conventional economic values.

Results of the analysis indicate that the domestic social costs are less than the economic benefits by more than three orders of magnitude, and that the permit option dominates those of delay or prohibit. An examination of proliferation risk indicates a factor of ~ 7 between cost-benefits. Thus, on the basis of this analysis, it appears that to permit reprocessing is optimal over delaying or prohibiting the technology.

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" . . .there is a maze of regulatory, technological, and business decisions that must be made by the government and the nuclear industry to close the back-end of the fuel-cycle. *I think the problem would be a challenge to those who like to do fault-tree analyses.* It's a nightmare for the decision-makers in government and industry."

--Major General Chapman (Retired)
Director of the Office of Nuclear
Materials and Safeguards
U.S. Nuclear Regulatory Commission

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SUMMARY

A. Introduction

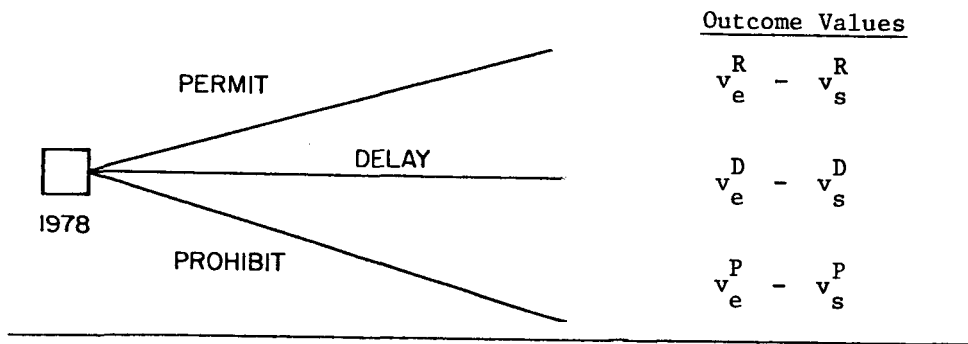
The Carter Administration has deferred nuclear spent fuel reprocessing on the grounds that there are low economic benefits from reprocessing and that the associated social costs are high. The Ford-Mitre study has also recommended the policy of delaying reprocessing until that time when the economic benefits can be shown to clearly outweigh the social costs. However, previous analyses of the reprocessing decision have not included the effects of uncertainty explicitly in their calculations of economic benefits, nor have they attempted to quantify the social costs arising from technological risks. This study explores the justification for the deferment policy by analyzing and comparing the social benefits of available reprocessing alternatives with their social costs.

B. The U. S. Reprocessing Decision

As of 1978, the U. S. reprocessing decision appears to involve a choice between three alternatives: (1) to *permit* the reprocessing of LWR spent fuel by licensing reprocessing plants for earliest operation by 1985, (2) to *delay* the decision until a later date, and (3) to *prohibit* reprocessing by passing a law against its use (Fig. S.1). Outcome values associated with each decision alternative are classified into social benefits and costs. Social benefits refer to those consequences of a decision that affect society advantageously, while social costs refer to those consequences that adversely affect society. Following the logic of social benefit-cost analysis, the preferred alternative is that which exhibits the largest positive difference between the social benefits and costs. In this case, society is defined to become "better off" as a result of the decision.

The principal social benefit of reprocessing is the potential to reduce electricity costs to the consumer. This benefit is denoted v_e for the value of the economic benefits arising between decision options. However, technological risks are also associated with each alternative. These risks include those related to health, the environment and safety, nuclear theft and sabotage, and nuclear proliferation. These risks translate into

Figure S.1 The U.S. Reprocessing Decision



dollar costs to society, denoted v_s for the value of the social costs arising between decision options.

C. The Use of Bayesian Decision Analysis to Encode Uncertainty

Because reprocessing economic benefits and social costs are uncertain quantities, a probabilistic approach has been taken to evaluate them. Bayesian decision analysis, a method capable of handling complex real-world decision problems, has been applied to incorporate explicitly the uncertainty surrounding key parameters. Uncertainty is encoded through the assignment of probability distributions over a wide range of plausible values on key variables. Called prior distributions, or simply "priors", these probability distributions reflect the best information available at the time the decision must be made. In this study, "base-case" priors reflect the author's interpretation of expert opinion expressed in the available literature.

To test sensitivity to these probability assignments, a stochastic analysis is conducted by sequentially assigning a certain value to each variable while adjusting all other priors on variables as necessary to reflect this certain value, and then recalculating the results. If the original order of the decision alternatives remains unchanged, the decision is said to be *insensitive* to changes in the state-of-information regarding key uncertainties; i.e., the decision is *robust*.

Outcomes of decision alternatives are expressed in expected value terms. The expected value criterion is a plausible one for decisions where adverse outcomes are much less than the total wealth of society, i.e., place at risk an acceptably small portion of society's assets. This is clearly the case with respect to reprocessing economic benefits. Annual expenditures in the nuclear fuel cycle represent less than 1% of the total U. S. gross national product (GNP) per year. It is shown in this study that outcome values associated with fuel cycle technological risks also satisfy this condition.

D. The Economic Value of Reprocessing Decision Alternatives

The reprocessing decision can impact upon the cost of electricity to the consumer in two ways: *directly*, by affecting the cost of LWR-produced electricity because of implied differences in LWR fuel-cycle costs, and *indirectly*, by influencing the commercialization date of the LMFB, thus affecting the long-term cost of electricity to the consumer.

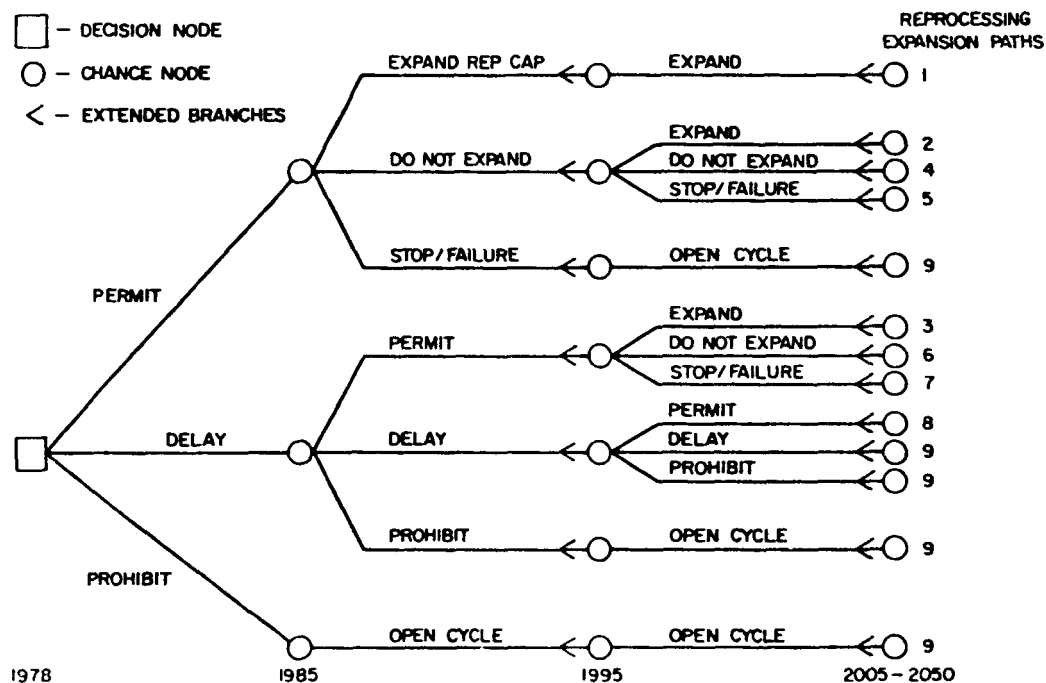
1. Direct Economic Benefits

To estimate *direct* economic benefits, LWR fuel cycle costs were calculated for each decision alternative and then compared. The reprocessing decision affects LWR fuel cycle costs because each decision option implies a different future for the nuclear fuel cycle industry. For example, a prohibit decision implies that the fuel cycle can evolve only in an open-cycle mode, while a decision to permit reprocessing implies that the industry can begin operation as soon as reprocessing capacity is made commercially available. A reprocessing delay implies that the government must face the prohibit/permit decision at a later date; in the interim, the LWR fuel cycle continues operation in an open-cycle mode.

An event tree description of future reprocessing industrial expansion paths was used to model these implications for nuclear fuel cycle growth, in addition to uncertainty on key parameters such as uranium supply and total electricity demand. Ranges of between 4 to 6 TkwH for year 2000 total electricity demand, 120-840 GWe installed LWR capacity for year 2000, 150-500 \$/kg HM reprocessing cost, and 35-100 \$/lb-U₃O₈ were used in establishing prior distributions.

A fuel cycle simulation model driven by LWR capacity and reprocessing expansion schedules was developed to calculate total fuel cycle system costs over the years 1975-2050 for each possible industrial expansion path represented in the event tree model (Fig. S.2). The tree was then "folded back" to derive expected value fuel cycle expansion costs for each decision option. These were then compared to derive direct economic benefits.

Figure S.2 Event Tree Model of LWR Fuel Cycle Industrial Expansion



In an attempt to show the effect of social time preference for benefits and costs, results are expressed both in undiscounted terms and also for a discount rate of 6%. At 6%, the permit option yields a present value of 11.9 billion dollars more benefits than from prohibit, representing a difference in nuclear electrical generating costs of 1.03 mills/kWh over the time span 1975-2050. The delay option exhibits 3.7 billion dollars worth of benefits over prohibit in present value terms and in 1975 dollars at a discount rate of 6%, or a .32 mills/kWh decrease in electrical

generating costs over the prohibit option. A stochastic sensitivity analysis revealed the insensitivity of the ranking of the decision alternatives to changes in key parameters, with permit remaining dominant over delay in all cases.

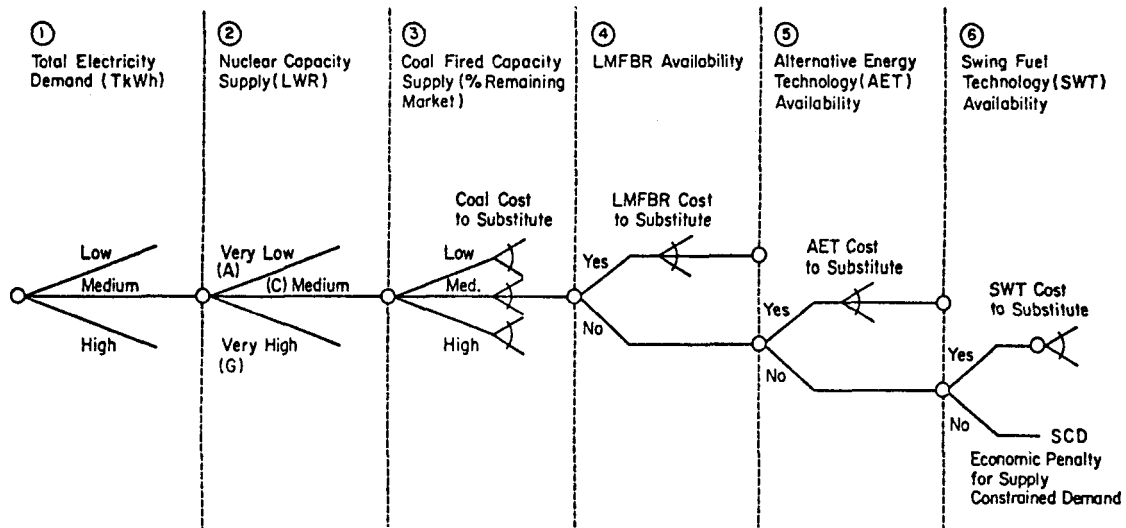
2. Indirect Economic Benefits

To assess *indirect* benefits, the LMFBR commercial introduction date was treated as a future uncertain variable with respect to the present administration of governmental decision-makers. Because the LMFBR is a reprocessing dependent plutonium based system, the reprocessing decision for LWR spent fuel carries major implications for the future commercialization date of the LMFBR. The likelihood that the LMFBR is introduced into the U. S. economy within a particular time period is considered conditional upon the reprocessing decision option chosen. Implied differences in the breeder introduction date translate into differences in breeder benefits to society, again reflected in the consumer's electricity bill.

An event tree description of U. S. electricity supply mixes was used to calculate indirect benefits (Fig. S.3). A range on electrical demand met by LWR capacity was established as a function of time, again over the time span 1975-2050. Then a range on electrical demand met by coal-fired capacity was estimated, with the remainder of demand assumed satisfied by swing fuels such as oil and natural gas, or alternative energy technologies (AETs). The AET is composed of advanced concepts such as central station solar power, fusion, or decentralized soft-energy technologies. In addition, the AET includes various converter-breeder combinations currently under study as proliferation-resistant alternatives to the LWR-LMFBR system. The likelihood of AET availability is expected to increase as time progresses, and oil and gas are gradually phased out as alternatives. Finally, for those scenarios in which demand exceeds supply, an economic penalty was assigned reflecting society's willingness to pay for additional capacity to meet the remaining demand.

Including the indirect effects, there are 71.9 billions of present value 1975 dollars at a discount rate of 6% over 1975-2050 for the permit option over prohibit, or a reduction in total electrical generating costs to the consumer of 6.25 mills/kWh. The delay option yields 38.6 billion

Figure S.3 Event Tree Description of U.S. Electricity Supply States-of-the-World *



*Time-Period 1: (1) 1975-1995, (2) 1996-2015, (3) 2016-2035, and (4) 2036-2050.

dollars worth of benefits over prohibit, or a reduction of 3.36 mills/kWh in electrical generating costs to the consumer as compared to the prohibit option. Over 95% of the benefits accrue beyond the end of the 20th century. This is because the LMFBR and AET are medium- to long-term alternatives. A stochastic sensitivity analysis indicated insensitivity of the decision to changes in key parameters affecting indirect benefits, again revealing the dominance of the permit option over those of delay or prohibit.

E. The Social Costs Associated with Reprocessing Decision Alternatives

Three categories of technological risk associated with reprocessing decision alternatives have been analyzed: (1) *health, environmental, and safety*, (2) *nuclear theft and sabotage*, and (3) *nuclear proliferation*. In quantifying social costs due to these risks, emphasis is placed on society's willingness to pay to reduce risk to some implicitly acceptable level evidenced by risks society currently faces. The trade-off between risk reduction and health, safety, safeguards and arms control expenditures

follows the economic law of diminishing returns; the marginal return per dollar spent decreases as the total expenditure increases. The question becomes one of determining the level at which the marginal return per unit cost can no longer justify the continued expenditures, a social value judgment.

1. Social Costs Arising from Health, Environmental, and Safety Technological Risks

The nuclear fuel cycle, regardless of *modus operandi*, poses risks to the environment and to the health and safety of persons employed at or living near fuel-cycle facilities. A review of recent studies was undertaken to determine differences in *health, environmental, and safety risks*. It was found that safety risks in the fuel cycle are dominated by those in the reactor, and that safety risks are themselves dominated by health risks. The major component of health risk is attributed to occupational routine exposure to low-level radiation. A comparison of study results rendered an estimate of .2 to .8 person-REM per MWe-year as the health effect from routine radiation exposure. Using a value of 30-100 \$ per person-REM, the social cost per GWe-year was estimated to be on the order of 6 to 80 thousand dollars (1975 dollar terms), with the inclusion of effects to offsite populations roughly doubling this estimate. Moreover, studies conclude that the differences in health, environmental, and safety risks between open and closed cycles are negligible. An American Physical Society study states that, with fuel reprocessing and recycle, potential improvements in health and safety result from decreases in uranium mining and milling. Thus, it was concluded that health-, environmental-, and safety-related social costs between reprocessing decision options are essentially the same, implying zero differential social costs v_s .

2. Social Costs Arising from Nuclear Theft and Sabotage Technological risks (Safeguards Assessment)

A safeguards assessment methodology was developed to quantify the social costs due to *nuclear theft and sabotage risks*. Event trees describing potential acts of nuclear theft-sabotage were constructed by defining

Table S.1

COMPARISON OF EXPECTED VALUE ECONOMIC BENEFITS WITH DOMESTIC SOCIAL COSTS
(1975-2050)

A. In Billions of 1975 Dollars at Discount Rate of 0% and 6%.

Decision Options Outcome Values	Permit		Delay		Prohibit	
	0%	6%	0%	6%	0%	6%
1. Benefits						
-- Direct	65	11.9	23	3.7	0	0
-- Indirect	1600	71.9	916	38.6	0	0
Total (v_e)	1665	83.8	939	42.3	0	0
2. Costs						
--HE&S	0 (1.7)	0 (.31)	0 (1.7)	0 (.31)	0 (1.7)	0 (.31)
--NT&S	.0017 (.0033)	.0002 (.0004)	.0006 (.0022)	.0001 (.0003)	0 (.0016)	0 (.0002)
Total (v_s)	.0017	.0002	.0006	.0001	0	0
3. $v_e - v_s$	1665	83.8	939	42.3	0	0

B. In mills/kWh for a Capacity Factor of 60% during an Average Year at Discount Rate of 0% and 6%.

Decision Options Outcome Values	Permit		Delay		Prohibit	
	0%	6%	0%	6%	0%	6%
1. Benefits						
--Direct	1.24	1.03	.44	.32	0	0
--Indirect	30.43	6.24	17.43	3.36	0	0
Total (v_e)	31.67	7.27	17.87	3.68	0	0
2. Costs						
--HE&S	0 (.03)	0	0 (.03)	0	0 (.03)	0
--NT&S	.00003 (.00006)	.000025	.000015 (.000045)	.000011	0 (.00003)	0
Total (v_s)	.00003	.000025	.000015	.000011	0	0
3. $v_e - v_s$	31.67	7.27	17.87	3.68	0	0

* Discounted to year 1975 @ 0% and 6%. Values in parentheses denote actual social costs used to determine differential social cost values shown.

three categories of events: (1) pre-initiation events, which *precede* an act of nuclear theft or sabotage, such as gaining access to technical information, organizing the attack or saboteur group, acquiring necessary equipment, etc., (2) initiation events, which *constitute* an actual act of nuclear theft or sabotage, such as entry to site, entry to facility, overcoming guards, disconnecting alarms, etc., and (3) post-initiation events, which take place *after* a successful theft of nuclear material, such as dispersal of toxins, processing of material for use in explosives, etc.

Differences between open and closed fuel cycles as they affect theft and sabotage risk were examined on a facility-by-facility basis: (1) reprocessor-MOX fabricator in comparison with a spent-fuel temporary storage repository, and (2) MOX fuel transportation compared with high-level waste and ten-year-old spent fuel transportation. On the basis of likelihoods assigned to events (reflecting the author's interpretation of the available literature concerning safeguard system reliability, design layout, personnel required for explosive construction, etc.), event trees were "folded back" to arrive at expected value consequences. Comparing these estimates for both the closed and open cycles rendered differential social costs of 76-142 \$ per GWe-year, with the open cycle exhibiting the lower costs. On a mills/kWh basis, this cost represents a mere 10^{-5} mill/kWh, a very insignificant cost to the consumer of electricity.

3. Comparison of Domestic Social Costs with Economic Benefits Associated with Reprocessing Decision Alternatives

Comparing the domestic social costs due to health, environmental, and safety (HE&S) risks and nuclear theft and sabotage (NT&S) risks with the economic benefits, it appears that the permit option exhibits the largest positive margin over the costs (Table S.1). The results are expressed both in present worth billions of 1975 dollars at discount rates of 0% and 6%, and also in mills/kWh. It appears that domestic social costs are dominated by economic benefits, expressed as the differential benefits-costs between the closed and open fuel cycles.

F. The U. S. Reprocessing Decision Inclusive of Nuclear Proliferation Risk

1. Perspectives on Proliferation Risk

The third category of technological risk associated with reprocessing alternatives relates to *nuclear proliferation*, defined as the acquisition, development, and construction of a nuclear weapon(s) by a formerly non-weapons state. The relationship between nuclear proliferation and world order and stability is not agreed upon. Opinions range from those who claim proliferation will produce large, adverse effects to those who claim that proliferation will produce beneficial effects. The first group of observers see the probability of nuclear war increasing with proliferation because of what they feel will be an increase in regional conflicts culminating in nuclear war, while the second group see the probability of nuclear war decreasing because of the growth of counter-balancing nuclear powers and an equalization in world power and economic prosperity.

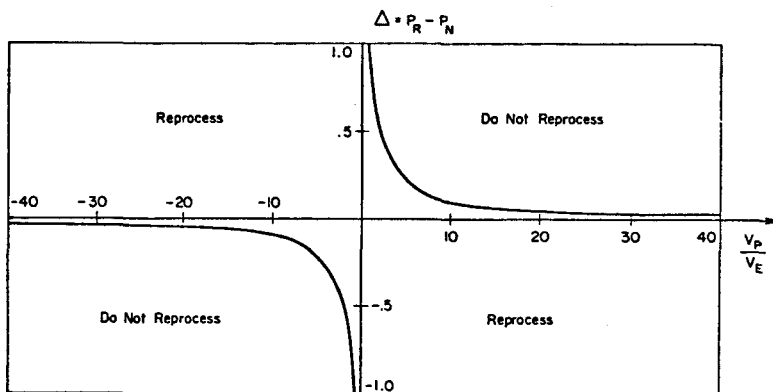
Equally varied and diverse are the opinions concerning the influence of the U. S. reprocessing decision on future proliferation events outside the U. S. Some observers claim that the widespread deployment of reprocessing and the breeder, with the attendant plutonium economy, will increase the likelihood of proliferation because of an increase in the availability of weapons-usable material on a world-wide scale. Others claim that, without reprocessing and the breeder, non-weapons states will be tempted to acquire weapons because of the exacerbation of the global energy crisis. A third group assert that proliferation effects could go either way, that world institutions will adapt as necessary as new weapons states emerge, and that proliferation is little affected by U. S. decisions regarding domestic civilian commercial nuclear power.

2. A Decision Model Inclusive of Proliferation Risk

Proliferation can occur regardless of whether or not the United States decides to reprocess its spent fuel in the near future. Thus, the U. S. decision as to whether to permit or delay (or prohibit) reprocessing can be summarized as a choice between two lotteries, denoted L_1 and L_2 , where each lottery includes an outcome value related to proliferation, denoted

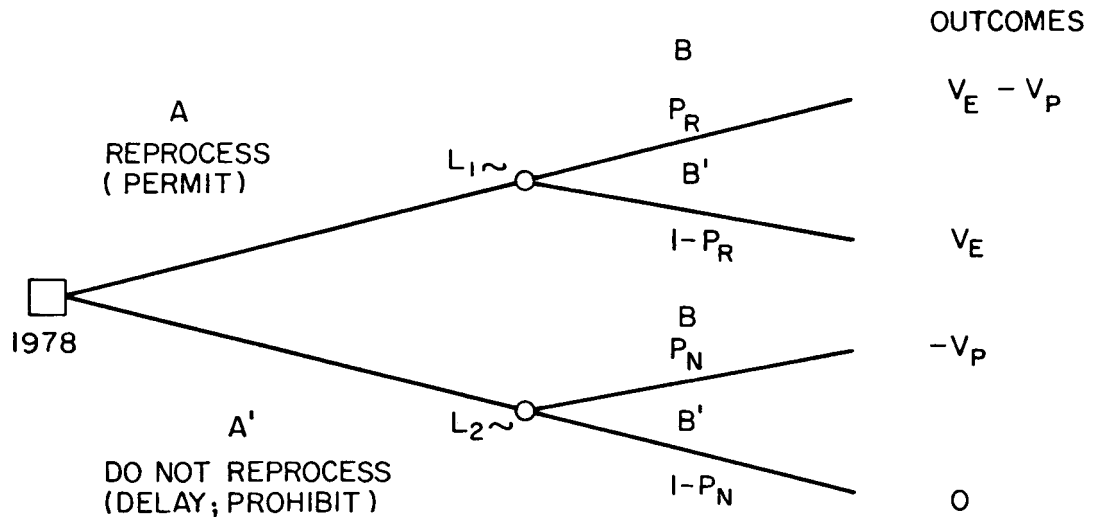
v_p , the dollar value of non-proliferation (Fig. S.4).^{*} The permit lottery L_1 includes a second outcome, v_E , defined as the differential economic benefits between permit versus delay (or prohibit) options. The probabilities associated with proliferation are denoted P_R and P_N , where P_R is the probability that an event of proliferation will occur within a given year if the U. S. permits reprocessing, and P_N the probability of such an event if the U. S. does not permit reprocessing. The decision to permit reprocessing would make sense if lottery L_1 is preferred to lottery L_2 . This is the case if the inequality $v_E > \Delta \cdot v_p$ holds true where $\Delta = P_R - P_N$, the differential likelihood of proliferation between decision options. The "break-even" curve $v_E = \Delta \cdot v_p$ defines those points for which the expected value outcomes of reprocessing are equivalent to those of not reprocessing. This curve represents a rectangular hyperbola for any constant value of v_E derived from the economic models, and defines a policy-region diagram where the decision to permit reprocessing is preferable if $1/\Delta > v_p/v_E$ (Fig. S.5). Having established the general decision framework, it is now necessary to examine both the value of non-proliferation v_p and also the differential likelihood of proliferation Δ between decision options.

Figure S.5 U.S. Reprocessing Decision Policy Region Diagram



*The analysis here examines the options of whether or not to permit reprocessing, where not permitting reprocessing in the immediate future corresponds to either an indefinite deferral or delay of the decision, or to a complete prohibition. The question examined is how such alternatives affect the likelihood of a future event of proliferation, defined as the emergence of one additional weapons state.

Figure S.4 U.S. Reprocessing Decision Inclusive of Proliferation



*

Note: v_p : Value of Non-Proliferation

v_E : Value of Economic Benefits Between Decision Options

P_R : Probability of Proliferation with Reprocessing

P_N : Probability of Proliferation with No Reprocessing

L_1, L_2 : Lotteries; A, A', B, B' : Events

3. The Value of Non-Proliferation (v_p)

The *value of non-proliferation* v_p is interpreted as the dollar amount that U. S. society would be willing to pay now (as of 1978) to reduce the likelihood of a future event of nuclear proliferation.* That is, v_p is viewed as an expenditure made by society on an annual basis to reduce the likelihood of proliferation events occurring within that particular year. Since proliferation is a continuing risk, expenditures to reduce proliferation risk can be viewed as a time-stream of annual payments, fluctuating in magnitude from year to year, reflecting how the magnitude of the risk is viewed depending on what countries are involved. That is, the U. S. may be willing to pay more to prevent an unstable, unfriendly country from acquiring weapons as opposed to a potential ally. However much this time-stream of expenditures varies in magnitude, it can be equated to a series of annuities that remain constant over time. The equivalent constant annual payment is what is sought in defining a value for v_p .**

From this perspective, it is possible to bound v_p by recognizing that the U. S. cannot afford to spend more than its annual gross national product of two trillion dollars (as of 1978) to reduce proliferation risk. The tradeoff between available income and risk reduction defines a technical opportunity frontier (TOF) for a given organization that must face risks. Applied to society, the TOF would be established for a particular country as a function of its annual GNP, since the GNP establishes the greatest upper bound on funds available to reduce societal risks. Thus, proliferation risk is placed into perspective when it is recognized

* Implicitly, an assignment of a positive value to v_p implies that U.S. society views proliferation as an uncertain event that produces adverse effects to be avoided, while a negative value for v_p would imply that U. S. society views proliferation elsewhere as producing beneficial effects.

** Note that this interpretation of v_p corresponds to a similar treatment where a "certain equivalent" would be determined for the lottery representing the uncertain effects of a particular event of proliferation. That is, v_p is not interpreted as the expected value dollar consequence of all future events of proliferation, since that would require the modeling of all possible sequences and combinations of future proliferation events and their effects on world order, a formidable if not impossible task.

as only one among many risks society must face. That is, society must decide how much of its yearly income it is willing to divert to ensure that proliferation risk does not rise above some implicitly acceptable level, while ensuring that other societal risks do not increase unacceptably because of the diversion of funds to reduce proliferation risk. For example, if v_p is assigned a value equivalent to the yearly GNP, that would imply that society perceives proliferation risk as so greatly more threatening than all the other risks it faces that it would prefer to spend all of its income to reduce proliferation risk rather than spending anything on even the necessities of life, such as food, clothing, or shelter.

A more reasonable upper bound on v_p is established by examining what the U. S. currently spends to reduce risks associated with today's already proliferated world. One indication is the entire current annual national defense budget of 112 billion dollars. A reasonable lower bound might be 1% of this value, or 1 billion dollars per year. These bounds correspond to hypothetical tax increases for the average American family of between 20 to 2000 dollars per year.

To determine where in this range v_p might be expected to fall, U. S. response to past events of proliferation was examined -- for example, to the Indian detonation of 1973. Historical response indicates a yearly increase in the defense budget of some 6% per year, or roughly 6 billion dollars per year. It can be expected that changes in the rate of proliferation events would be reflected in an increase or decrease of this yearly expenditure, also in response to which country proliferates and when. To establish an estimate for v_p , future rates of proliferation are assumed greater than the historical rate, corresponding to annual expenditures of $\sim 10\%$ of the 1978 defense budget, or 12 billion dollars per year.* Alternatively, this value corresponds to a hypothetical

*This value may appear high to those who feel that the worst events of proliferation have already occurred; i.e., our worst enemies have already acquired nuclear weaponry. To others, this value may seem low if they perceive that future proliferating states will be harder to maintain stable relations with, or defend against.

increase in taxes of 240 dollars per year for the average American family.

A "break-even" estimate for the differential likelihood of proliferation, Δ , between decision options of 20% is implied by the 12 billion dollar per year estimate for v_p and the expected value estimate for the economic benefits v_E of 2.52 billion dollars per year.* This implies that only if Δ can be shown to be greater than 0.2 should the U. S. defer reprocessing on the basis of proliferation risk arguments, where Δ refers to the difference in proliferation likelihood between permit and delay options.

4. Identifying a Quantitative Estimate for Δ : the Differential Likelihood of Proliferation between Decision Options

Next, a quantitative estimate for Δ was obtained by examining some nine currently available routes to weapons material attainment. Research reactors (which over fifty countries now own and operate) and production reactors, when coupled to minimum plutonium-recovery plants (MPRPs), can be used to obtain weapons material. Commercial power plants, when coupled either to MPRPs or to commercial reprocessors, can also be used to acquire such material.** Enrichment technologies are also routes to such a goal. In the future, seven other routes may also become available, such as laser isotope separation, high-energy neutron sources like the fusion Tokamak machine, fission-fusion hybrid reactors, and the intense neutron generator accelerator.

* The estimate for Δ of 20% was derived from the "break-even" relation $\Delta = v_E/v_p$, where $v_E = 2.52 \times 10^9$ \$/yr, representing the annualized economic benefits between permit and delay options over the time-span 1975 to 2050 discounted at 6% to 1975. At a 6% discount rate, the annualized value v_E was derived as follows (see Table 1): $v_e^R = 83.8$ billion dollars; for delay, $v_e^D = 42.3$ billion dollars. Thus, $v_e^R - v_e^D = 41.5$ billion dollars. The capital recovery factor for 6% over 75 years is .0608, which multiplies the 41.5 billion dollar difference between permit and delay to arrive at the 2.52 billion dollar per year equivalent annual payment.

** It should be noted that commercial reactor-grade plutonium does not represent weapons-grade material in the classical definition of that term because of the high Pu-241 content present in LWR fuel. It is the case, however, that reactor-grade plutonium is weapons-usable.

Table S.2

RANKINGS OF CURRENTLY AVAILABLE ROUTES TO WEAPONS MATERIAL ATTAINMENT

I	Route	R_I^A	R_I^D	R_I^I	Relative Ranking (%)
1	Res Reac (+MPRP)*	.192	.189	.27	32.1
2	Prod Reac (+MPRP)	.186	.3	.05	25.5
3	Power Reac (+MPRP)	.077	.075	.27	10.3
4	(Power Reac +)Com Rep	.064	.075	.06	<u>3.4</u>
5	Diffusion Cascade	.071	.113	.1	5.9
6	Centrifuge Cascade	.115	.113	.1	9.5
7	Aerodynamic Jet	.102	.075	.1	7.0
8	Electromagnet Sep	.083	.04	.033	4.6
9	Accelerator	.110	.02	.017	1.6

$\Sigma = 1$ $\Sigma = 1$ $\Sigma = 1$ $\Sigma = 100\%$

where

R_I^A = ranks the relative attractiveness of Option I on the basis of cost, technical difficulty, material flow, time to weapon, etc.

R_I^D = ranks the relative domestic availability of Option I to the Nth country on a technical basis.

R_I^I = ranks the relative importability of Option I (or the market availability abroad).

$$\text{Relative Ranking (\%)} = ((1-R_I^D) \cdot R_I^I + R_I^D) \cdot R_I^A \cdot (\text{Sum Rel. Rank.}_I)$$

* Assumes Minimum Plutonium Recovery Plant (MPRP) can be constructed by the Nth country without foreign assistance; rankings are estimates for reactors themselves except in the case of the power-reactor/commercial reprocessing route, where the ranking is for the reprocessor.

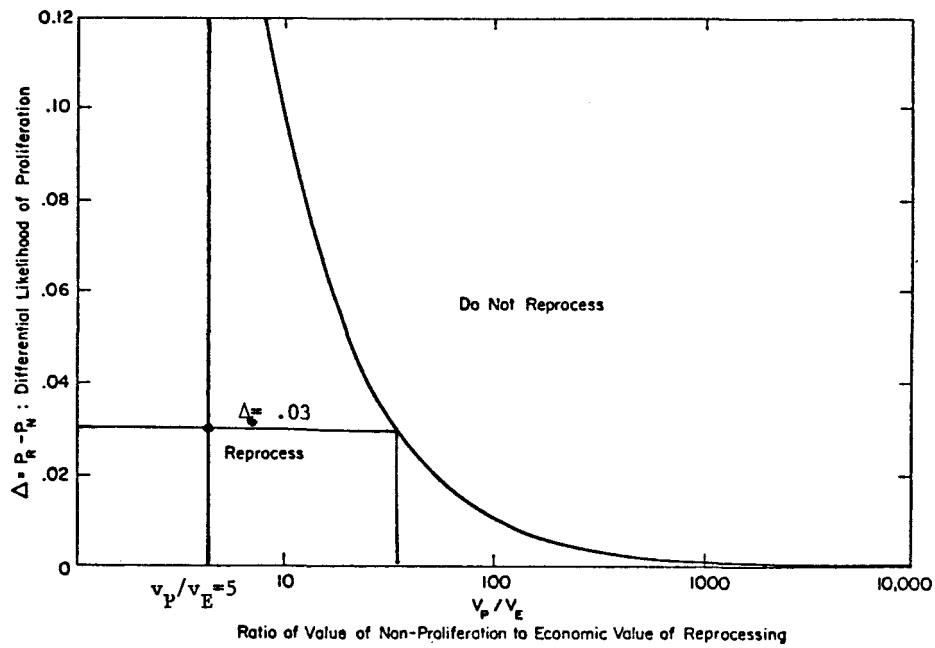
When a non-weapons state is considering these options, it is likely to examine the domestic availability of the technologies, their import availability, capital, operating and maintenance costs, in addition to their difficulty of technical implementation, suitability for clandestine operation, and the number of weapons obtainable from the material flow. The number of technical personnel required is also a consideration, along with the level of support technology and industry required. Each technological route was rated and compared on the basis of these multi-attributes to establish quantitative rankings of their relative attractiveness (Table S.2).*

The calculated rankings indicate the relative likelihood (as of 1978) that a nominal non-weapons state would choose a particular route to acquire weapons material over some other. The 3% ranking calculated for the commercial reactor-commercial reprocessor route is used as an upper bound estimate for Δ because it indicates the over-all relative attractiveness of the route to a non-weapons state desiring a minimal weapons capability. The estimate indicates that, at the next proliferation event, there is only a 3% chance that this might be attributed to the use of commercial reprocessing technology.

However, using the 3% estimate as an upper bound on Δ establishes a minimum estimate for the value of non-proliferation v_p . It indicates that non-proliferation would need to be valued by at least a factor of 33 times the economic benefits of reprocessing v_E , or $33 \times 2.52 \times 10^9$ \$/yr = 83 billion dollars per year before delay would be preferred over permit. This translates into a series of equivalent annual expenditures corresponding to a 75% increase per year in defense spending, a rate of increase that cannot be justified by historical experience. The relationship between these estimates for Δ and v_p/v_E is plotted in the expanded policy-region diagram which was derived earlier (Figure S.6).

* Data on each of the nine presently available routes to weapons material attainment came from four separate references: Lamarsh, from the OTA study for Congress; Science Applications, Inc., from the study done for Pan Heuristics; Ladesich for Westinghouse Corp.; and Zebroski and Starr at the Electric Power Research Institute. These data were used in establishing quantitative rankings for each route.

Figure S.6 Expanded Scale Policy-Region Diagram: Final Results



G. Conclusions

In summary, expected value total economic benefits and domestic social costs were calculated for each reprocessing decision alternative. It was shown that the domestic social costs are less than the economic benefits by more than three orders of magnitude, and that the permit option dominates those of delay or prohibit. Then, the differential economic benefit between permit and delay options was used to establish a "break-even" estimate for Δ , the differential likelihood of proliferation arising between decision options, defined from a simple

reprocessing decision model inclusive of proliferation risk. A value for Δ of 20% was obtained based on an estimate for the value of non-proliferation v_p of 12 billion dollars per year reflecting past historical experience. Finally, a technical assessment of currently available routes to weapons material attainment revealed the relative unattractiveness of the commercial power reactor/ commercial reprocessor route to weapons material. By comparing the 3% upper bound estimate with the "break-even" estimate for Δ of 20% obtained from the ratio v_E/v_p , a factor of ~ 7 is obtained, indicating that permit is preferable over delay. Thus, on the basis of this analysis, it appears that to permit reprocessing is optimal over delaying or prohibiting the technology, and that the deferment policy cannot be logically justified on the basis of nuclear proliferation arguments.

Chapter 1

THE REPROCESSING DECISION

Decisions are frequently postponed because of uncertainty surrounding possible consequences. Often, further research is requested in hope that uncertainties will be resolved. But the delay is often costly, and major uncertainties may not be resolved by the research. An example is the long-term management of spent fuel. As the decision on its ultimate disposition is delayed, spent fuel pools continue to fill. . . *We should not attempt to resolve all uncertainty before committing to decisions, but rather examine whether the cost imposed by delay will be counter balanced by expected improvements in our state-of-information.*

--Barrager, Judd and North [1]

Overview

Reprocessing is controversial.¹ Opponents view the technology as a threat to the environment and society. Plutonium, a reprocessing product, is described as "the most toxic substance known" for which spills, fires and thefts lead to environmental contamination [2,3]. In their view, the plutonium economy would strain world society and institutions to unknown limits, since stolen plutonium could be used by terrorists to manufacture nuclear bombs [4,5]. Finally, opponents fear that non-weapons states will divert plutonium from commercial reprocessors for weapons production, increasing nuclear proliferation rates [6,7].

Defending reprocessing, proponents stress the need to close the fuel cycle while nuclear power expands to meet global energy needs and other long-range technologies develop [8,9]. Plutonium hazard arguments are discounted: "scientific evidence indicates that plutonium as a

¹Reprocessing refers to the radio-chemical technology of treating light-water reactor (LWR) spent fuel to extract and separate recyclable materials from waste. In the LWRs of today, approximately 95% of the spent fuel is recoverable uranium, another 1% plutonium that can also be used for fuel, while the remaining 4% is high-level radioactive waste. Background to the reprocessing debate is provided by examining the United States history of nuclear power, detailed in Appendix A.

Table 1.1

PREVIOUS STUDIES*

Date of Study	Title	Net Reprocessing Benefits	Time Span of Study
1. April 1976	AGNS [13]	\$ 7.6 x 10 ⁹ @ 0%; 1976 \$	1980-2000
2. July 1976	Pan Heuristics [7]	Unspecified Negative Value	Not Dynamic
3. August 1976	GESMO [14]	\$ 3 - 6 x 10 ⁹ @ 10%; 1975 \$	1975-2000
4. December 1976	ERDA-76-121 [15]	\$ 2 x 10 ⁹ @ 10% 1977 \$	1976-2000
5. March 1977	V. Taylor [16]	-.4 x 10 ⁹ @ 10%; 1975 \$	1975-2000
6. December 1977	Manne-Richels** ETA-MACRO [17]	\$84 x 10 ⁹ @ 5% \$8 x 10 ⁹ @ 10% 1975 \$	1975-2050

* A comprehensive comparative treatment of previous reprocessing economic studies is found in the Atomic Industrial Forum publication of November 1977 entitled "Reprocessing - Recycle Economics" [47].

** To the author's knowledge, the Manne-Richels work is the only previous study to examine the economic relations between LWR reprocessing and delays in the commercialization of a plutonium-based breeder reactor.

hazard is no more dangerous to human health than any other chemicals we have learned to deal with" [10]. Proponents emphasize plutonium's importance as a reactor fuel, and postulate that, without reprocessing, nuclear growth will be severely constrained [11]. Further, because of extensive safeguard procedures, they regard the potential for illegal acquisition of plutonium to be negligible. Finally, proponents note that any nation can easily acquire weapons material by means other than commercial reprocessing at fractions of the cost and effort [12].

The purpose of this study is to analyze the United States reprocessing decision by estimating the social benefits-costs associated with currently available fuel cycle options, particularly examining the policy implications of nuclear proliferation, nuclear theft, and sabotage technological risks.

A. Previous Studies

Previous studies have not explicitly included the effects of uncertainty in their calculations of reprocessing economic benefits (Table 1.1). Moreover, they have not attempted to quantify the social costs of reprocessing for direct comparison with the benefits. Results of these studies place the economic benefits in a range from a low of a 400 million dollar loss (discounted at 10% to the year 1975 over the time span 1975-2000) to a high of a positive 8 billion dollars (discounted at 10% to the year 1975 over the time span 1975-2050). These differences are partially accounted for by variations in assumptions about costs, demand levels, and model time span. With the exception of Taylor [16], all studies attribute positive net benefits to reprocessing, and indicate the effect of delay is to reduce these benefits. All studies make judgmental cost estimates based on industrial-laboratory data and forecasts. However, they do not treat these costs as explicit uncertain variables. Consequently, a decision-maker may become confused because of the disparity between results. The failure to treat the decision in a probabilistic way reduces the value of these studies, and is a principal motivation for the present work.

B. Decision-Making Under Uncertainty: Bayesian Decision Theory and Decision Analysis

Increasingly, nuclear energy is being used to generate electricity worldwide [18], although debate exists over the market percent nuclear will command.² However, in order to sustain growth, decisions affecting fuel-cycle investments must soon be made. Long construction times require that decisions be made ten to fifteen years prior to the time additional capacity is required. As a consequence, uncertainty surrounds issues pertinent to the making of these decisions. In order to determine the best decision, a framework that incorporates key uncertainties must be developed that can balance economic benefits with social costs.³

The reprocessing decision can be classified as a "top management" (indeed, presidential) decision, which is characterized by: (i) uniqueness -- each decision is one of a kind, perhaps similar to, but never identical to, previous situations, (ii) importance -- a significant portion of the organization's resources is in question, (iii) uncertainty -- many of the key factors that must be taken into account are imperfectly known, (iv) long-run implications -- the enterprise will be forced to live with the results of the situation for many years, perhaps even beyond the political and business careers of the major

²This does not imply, however, that a zero likelihood can be assigned to the event of a domestic nuclear moratorium (see Chapter 3, Part A).

³The framework need not be capable of handling ethical considerations, such as those expressed by Kneese [19]:

"It is my belief that cost-benefit analysis cannot answer the most important policy questions associated with the desirability of developing a large-scale, fission-based economy. To expect it to do so is to ask it to bear a burden it cannot sustain. This is so because these questions are of deep ethical character. Cost-benefit analysis certainly cannot solve such questions, and may well obscure them. . ."

Ethical considerations are the domain of the political leadership and not the cost-benefit analyst. In the end, this study must be evaluated by political leaders and other government decision-makers; they may wish to disregard the narrowly economic results. The analyst can only indicate what the decision-maker should do to be consistent with the axioms of logical choice.

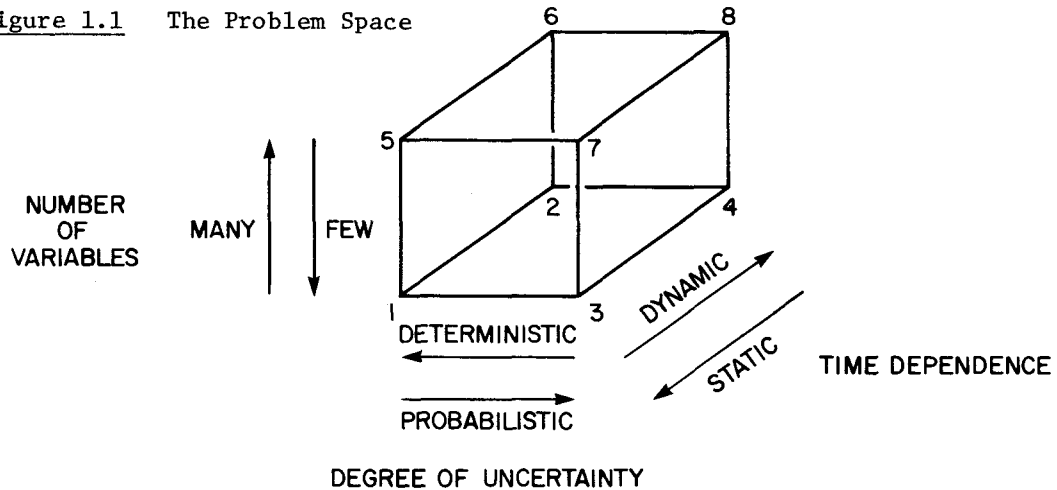
individuals involved, and (v) complex preferences -- the task of incorporating the decision-maker's preferences about time and risk assumes great importance [20]. Traditional deterministic models cannot alone be used to find solutions to these types of problems. Neither can statistical decision theory models that address simple uncertain situations. Instead, a method is needed that can handle complex, dynamic, and uncertain problems.

Decision analysis is such a method; it represents the merger of Bayesian decision theory and systems analysis. The complex and dynamic components of the problem are handled by systems analysis methods, while uncertainty is treated from a Bayesian perspective. A principle of decision analysis is that any information pertaining to the decision can be included through an inference process; *a decision can be made given any state-of-information*. This principle is based upon the Bayesian school of statistics that conceives of probability as a state-of-mind rather than a state-of-things (such as mass, shape, or color). To Bayesians, a probability is a numerical assignment measuring the state-of-knowledge concerning a phenomenon. The Bayesian, or inferential, theory of probability determines how the assignment fluctuates as a function of new data through Baye's Theorem on conjugate distributions. As a result, the value-of-experimentation, or *value-of-further-information*, can be evaluated.

A decision is defined as "an irrevocable allocation of resources where it is impossible, or extremely costly, to change back to the original situation existing prior to the decision" [21]. A good decision is defined to be logical and consistent with the values and preferences of the decision-maker. Decision analysis balances the values and preferences in a logical model of the decision suitable for computation and manipulation. The method places a premium on conceptual completeness, so that major issues pertinent to the decision are assured of inclusion.

A decision problem is defined by its underlying structure. The degree of uncertainty is one component of the structure; another, the number of variables. A third component is time. Problems can be categorized with respect to these three components defining a feasible set of problems, or problem space (Figure 1.1). Each of the axes describing the problem space represents a branch of mathematics, with the exception

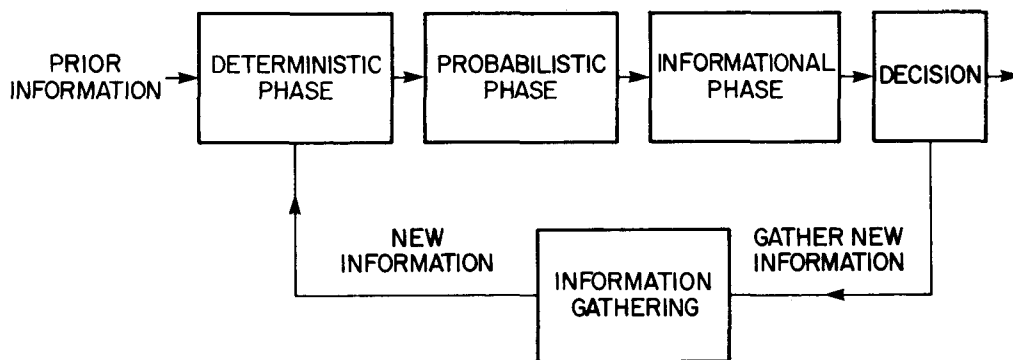
Figure 1.1 The Problem Space



of Corner 1, the domain of the "trivial" problem. Corner 2 represents the deterministic, dynamic one-variable problem solved by differential equation theory. Elementary probability theory handles the probabilistic, static, one-variable problem found in Corner 3. The probabilistic, dynamic, one-variable problem of Corner 4 is the subject of stochastic process theory, while the deterministic, static, multi-variable problem of Corner 5 is handled by matrix theory and multi-variate calculus. In Corner 6 are found the deterministic, dynamic, multi-variable problems treated by control theory and dynamic mathematical programming. Corner 7 includes the probabilistic, static, multi-variable problem studied in joint distribution theory. Finally, Corner 8 represents the most complicated of all problems; the probabilistic, dynamic and multi-variable problem for which the Markov process and its relatives are useful models. Corner 8 is also the domain of many real-world decision problems, including the reprocessing decision. For this reason, decision analysis is used since it is a method capable of handling such problems [21] .

The decision-process can be modeled in cyclical form (Figure 1.2). A deterministic phase driven by prior information, the initial state-of-information, consists of a deterministic model whose output is used in the probabilistic phase. In the informational phase, a sensitivity analysis is conducted. In this work, the models developed to analyze the reprocessing decision are based upon this cyclical representation of the decision-process.

Figure 1.2 The Decision Analysis Cycle [21]



C. Social Cost-Benefit Analysis

One question facing social decision-makers is: "How much should we as a society sacrifice *now* in order to make future generations better off?" [22]. If the time-discounted social benefits of a given project are greater than the time-discounted social costs, summed over all individuals in the society and over time, then the project is said to be socially beneficial. That is (where r is the social discount rate), if

$$\sum_{\text{Individuals}} \sum_{\text{Time}} \frac{\text{Benefits}^t}{(1+r)^t} > \sum_{\text{Individuals}} \sum_{\text{Time}} \frac{\text{Costs}^t}{(1+r)^t}$$

then there exists a *potential Pareto improvement*; society becomes better off as a result of the project. A decision made on this basis is said to satisfy the condition of Pareto optimality. The application of this theory is called cost-benefit analysis which was first applied in the United States to evaluate public works projects as a result of the Flood Control Act of 1936 [23].

In principle, the theory of cost-benefit analysis appears simple and straightforward. However, difficulties arise in application when defining benefits and costs and to which groups in society they apply. Troublesome and controversial matters include the selection of a discount rate to use in social decisions (see Chapter 3 for further discussion), selecting an appropriate numeraire, and deciding what public consequences are relevant to the evaluation.

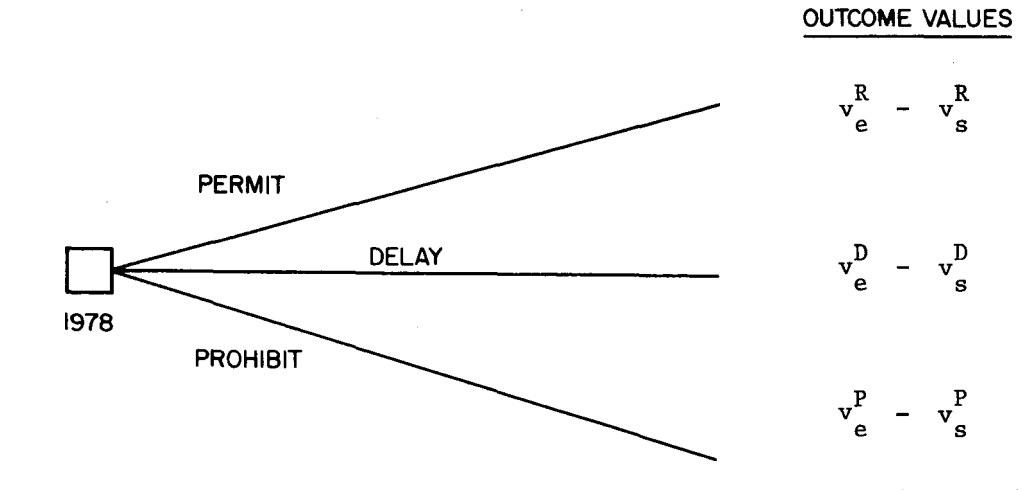
Social value judgments are made explicit in this analysis by assigning dollar values to social consequences. These assignments are not intended as objective measurements of society's value on lives, health effects, or national security for example. Rather, they are implied in the decisions that society makes regarding *how much it is willing to pay to reduce risks* from social hazards arising from a particular decision alternative.

D. The Reprocessing Decision Model

As of 1978, the U.S. reprocessing decision appears to involve a choice between three alternatives: (1) to *permit* the reprocessing of light-water reactor spent fuel by licensing reprocessing plants for earliest operation by 1985, (2) to *delay* the decision until a later date, and (3) to *prohibit* reprocessing by passing a law against its use (Figure 1.3). Outcome values associated with each decision alternative are classified into social benefits and costs. Social benefits refer to those consequences of a decision that affect society advantageously, while social costs refer to those consequences that adversely affect society. Following the logic of social cost-benefit analysis, the preferred alternative is that which exhibits the largest positive difference between the social benefits and social costs. In this case, society is defined to become "better off" as a result of the decision; there exists a potential Pareto improvement in social welfare.

The principal social benefit of reprocessing is the potential to reduce the cost of electricity to the consumer, denoted v_e for the value of the economic benefits arising between decision options. However, technological risks are also associated with each alternative. These include health, environmental and safety risks, nuclear theft and sabotage risks, and the risk of nuclear proliferation. These risks translate into dollar costs to society, denoted v_s for the value of the social costs arising between decision alternatives.

Figure 1.3 The Reprocessing Decision Model



Outcomes of decision alternatives are expressed in expected value terms, reflecting society's risk attitude toward decisions where outcomes are much less than the total wealth of society; i.e., place at risk an acceptably small portion of society's assets. This is clearly the case with respect to reprocessing economic benefits, since annual expenditures in the nuclear fuel cycle represent less than 1% of the total U.S. gross national product (GNP) per year. It is shown in this study that outcome values associated with fuel cycle technological risks also satisfy this condition.

The reprocessing decision can impact upon the cost of electricity to the consumer in two ways; *directly*, by affecting the cost of LWR produced electricity because of implied differences in LWR fuel cycle costs, and *indirectly*, by influencing the commercialization date of the LMFBR, thus affecting the long-term cost of electricity to the consumer. These categories of economic benefits, termed direct and indirect, are examined in the first few chapters of this thesis. The remaining chapters examine the three categories of technological risk that have been associated with reprocessing alternatives, beginning with health, environmental and safety risks, then examining nuclear theft and sabotage risk in the fuel cycle, and finally moving on to examine the trade-off between economic benefits and the risk of nuclear proliferation.

Chapter 2

THE NUCLEAR FUEL CYCLE

In 1972, French scientists discovered that in an uranium mine in Oklo, Gabon, several natural reactors had operated some 1.8 billion years ago, when the concentration of U-235 was 3% -- not .7%. The reactors operated intermittently over 500,000 years; they produced as much energy as a 1000 MW PWR operating for three years; and they produced five tons of fission products; about 2 tons of Pu-239. In this sense, nuclear reactors present less foreign intrusion on the earth than do some of the new chemicals which the earth has never seen before. . .

--Alvin Weinberg [25]

Overview

Currently, light water reactors dominate the United States nuclear sector. Breeder reactors are unlikely to be commercialized until after the year 2000, implying the continued dominance of LWR technology¹. This chapter reviews the history and describes the technologies of the LWR fuel cycle.

A. Historical Background [26]

The United States nuclear fuel cycle developed during the war years of the 1940's as a consequence of nuclear weapons development. Two paths were followed: one was to enrich uranium to weapons grade concentrations, the other was to fabricate natural uranium into fuel elements to be irradiated in production reactors to create plutonium. The plutonium product was separated from the uranium in chemical reprocessing plants and made into components for use in weapons. The wastes from the reprocessing plants containing highly radioactive fission products were (and still are) stored as liquids in large steel tanks.

¹The fuel cycle of the fast breeder reactor (FBR) is essentially the same in concept as that of the LWR operating with plutonium recycle. The various processes involved may be modified as necessary for breeder fuel.

Uranium needed for both processes was mined and utilized from Africa, the United States, and Canada. The industrial processing operations were carried out at vast installations located in remote areas in the United States. Major American businesses developed, designed, built and operated these facilities under the direction first of the United States Army Corps of Engineers and later of the U. S. Atomic Energy Commission (USAEC). All of the nuclear fuel cycle operations related to weapons production were carried out under tight government security regulations.

Out of these war-time operations emerged the organizations, technical personnel, technology and experience which later permitted the development of the U. S. Naval nuclear propulsion program and civilian reactor programs. The nuclear fuel-cycle facilities remained under the control of the USAEC. This happenstance created a strong industrial dependence upon government facilities which were hidden, under security regulations, from the public view. The Congress, through the Joint Committee on Atomic Energy, monitored and supported the use of resources and facilities needed to satisfy military requirements while, at the same time, encouraging the development of nuclear power for civilian use under the Atomic Energy Act of 1954.

Following World War II, the United Kingdom, France, the U.S.S.R. and China established programs for the production of weapons while beginning programs for peaceful applications of nuclear power as well. Canada, Japan, West Germany, Italy and Sweden decided against the development of weapons, but nonetheless developed a civilian nuclear electricity industry. Additional countries have followed the example of this latter group of countries, indicating the widespread acceptance of civilian nuclear power.

B. Process Descriptions

Nuclear fuel-cycle activities may be divided into front- and back-end operations. The front-end refers to those processes which are involved in the production of the *fresh* fuel to be inserted in the reactor.* These include: (i) uranium exploration, mining and milling, (ii) conversion, (iii) uranium isotope enrichment, and (iv) fuel fabrication. Those activities which make up the back end of the cycle are: (i) fuel reprocessing & recycling, (ii) plutonium storage, (iii) spent fuel storage and transportation, (iv)

* "Fresh" fuel refers to unirradiated fuel, the opposite of "spent" fuel that has recently been discharged from the reactor.

temporary waste disposal and management, and (v) permanent waste disposal and management. The LWR fuel cycle can operate either on a once-through completely uranium cycle, or on a mixed-oxide (MOX) cycle wherein uranium and plutonium are both used as fuels (Figure 2.1).

1. Uranium Mining and Milling

Uranium is found as a naturally occurring mineral in various forms in the earth's crust. The percentage concentration of uranium in any ore is small. Concentrations of two to five pounds of uranium per ton of ore are common in commercial grade ores. Uranium ores are located both in deep deposits, which have to be mined through conventional underground means, and in deposits near the surface, which can be mined as open-pits. The equipment and labor used in the development and production of uranium deposits are similar to those used in the coal industry. Once mined, uranium ore is processed in a mill that uses a number of conventional, mechanical and chemical steps to separate the uranium from the host rock and other minerals. The uranium is recovered as yellow cake; a uranium salt containing between 70 and 80% U_3O_8 . The development of a uranium mining and milling complex takes approximately ten years from initial exploration to full production.

2. Conversion of Uranium

The next step in the fuel cycle is the chemical conversion of yellow cake into a form suitable for the enrichment process. This form is the volatile compound uranium hexafluoride (UF_6). The conversion process involves three steps and concludes with a high-temperature fluorination stage.

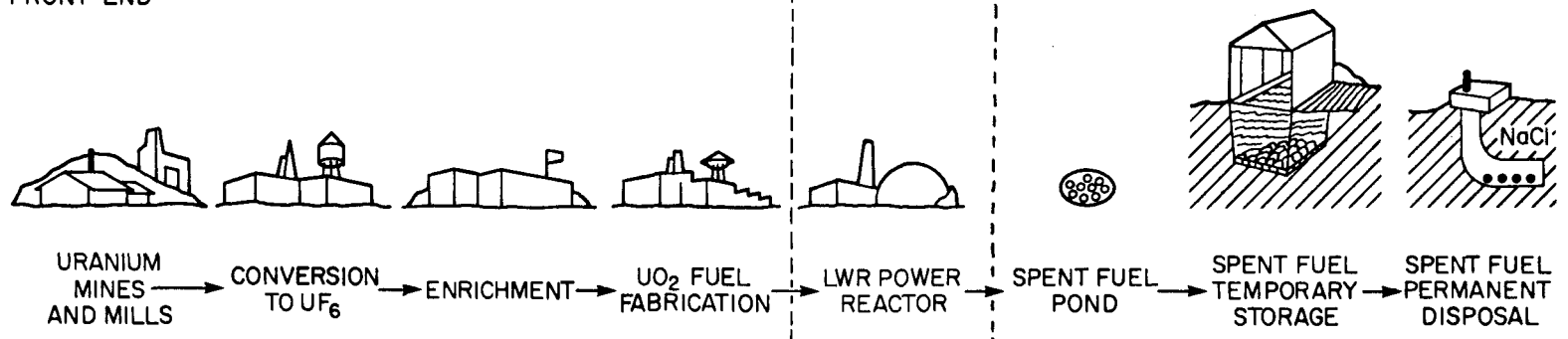
3. Enrichment -- Isotope Separation

Enrichment raises the isotopic concentration of U-235 in naturally occurring uranium. This process is necessary because a concentration of about 3% U-235, the *fissile* isotope in natural uranium, is required to sustain a critical fission reaction in a thermal reactor moderated with

Figure 2.1 Light Water Reactor (LWR) Fuel Cycle

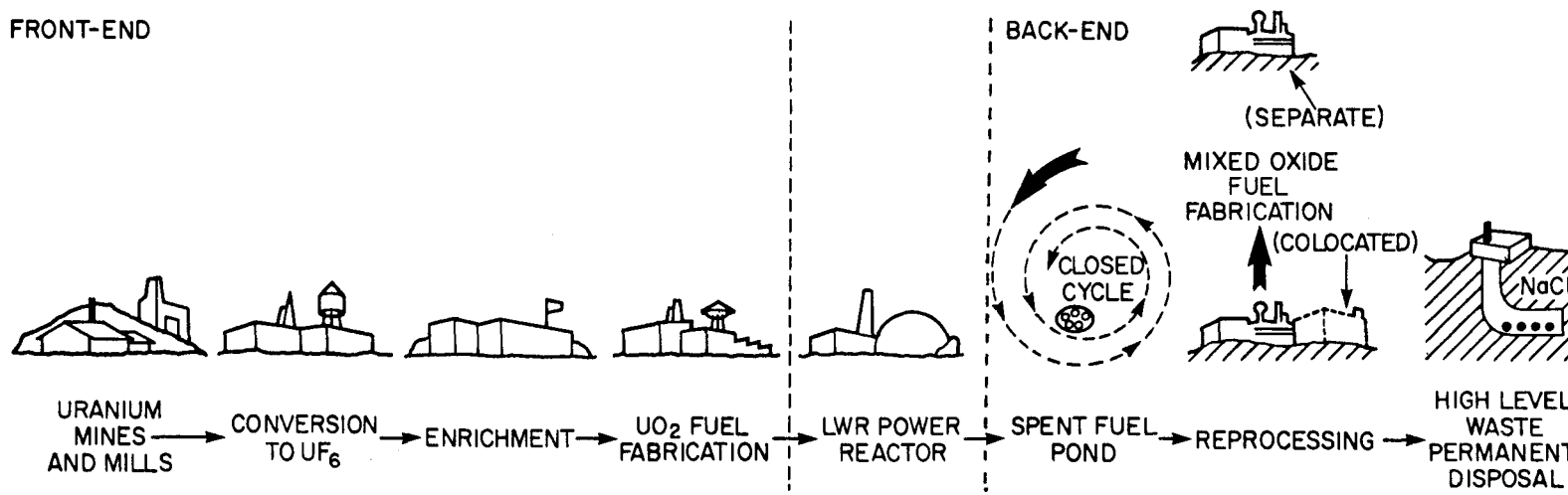
A. OPEN CYCLE (UO₂ FUEL)

FRONT-END



B. CLOSED CYCLE WITH PLUTONIUM RECYCLE (MOX FUEL)

FRONT-END



light water (H_2O).² The enrichment process is not necessary to prepare fuel for a heavy-water (D_2O) moderated reactor, such as the CANDU reactor of the Canadians, because criticality can be reached and maintained using natural uranium. However, heavy water must be extracted from natural water using a process that is relatively expensive. On the other hand, to use inexpensive light water as moderator requires that natural uranium be enriched to a higher U-235 concentration.

The most well-developed and widely used method of enrichment today in the United States is the gaseous diffusion process. This method makes use of the differences in rates at which gases of different molecular weight diffuse through a porous barrier. The other method of enrichment currently planned for use in the United States is the gas centrifuge method, already commercialized and operating in Europe. The principle of centrifuge enrichment is based upon the fact that the centrifugal force acting on a gaseous molecule varies with the molecular weight of the molecule. There are differences between centrifuge and gaseous diffusion technologies. The centrifuge requires only about one-tenth the electrical energy of the diffusion process, and the centrifuge is more adaptable to small-scale operation. Other enrichment methods include the laser and Becker nozzle methods, both under development in various laboratories worldwide.

The amount of U-235 required in the product stream affects both the amount of work required (expressed in separative work units (SWU)), and the amount of uranium feed required.³ Thus, by lowering the concentration of U-235 in the tails stream (i.e., varying the tails assay), feed

²U-235 is called a *fissile* isotope because it can fission after the absorption of a zero energy (or thermal energy) neutron. In contrast, U-238, the dominant isotope contained in natural uranium ($\sim 99\%$), is not fissile at thermal energies. However, at higher neutron energies of .5 MeV and greater, U-238 can be induced to fission, and so is known as a *fissionable* isotope. The U-238 isotope is also *fertile* because it can be converted into a fissile isotope (Pu-239) through the capture of a neutron in the (n, γ) reaction. It is this fertile property of U-238 that makes it attractive as a blanket material for fast breeder reactors in the production of large amounts of Pu-239.

³A separative work unit can be thought to represent the work required to convert one kilogram of natural uranium (.7% U-235) into ~ 0.2 kilograms of 3% enriched material at a tails assay of .2%. There are three material flows present in an enrichment plant, the feed stream referring to the material being input into the plant, the product stream which refers to the useful output (the enriched material), and the tails stream which refers to the depleted material that is not useful for LWR fuel fabrication.

material is more effectively utilized at the expense of higher energy consumption per unit enriched product. Current tendencies are moving in this direction in response to a limited uranium supply. It is estimated that the development of a new, full-scale enrichment plant today requires from eight to twelve years.

4. Fabrication (UO₂ Fuel)

The final step in the front end of the fuel cycle is fabrication. The enriched uranium is converted into small ceramic pellets of uranium dioxide. These pellets are then inserted into an assembly structure. When this is completed, the assembly is ready for shipment to the nuclear power plant. Under today's regulatory climate, a UO₂ fabrication plant takes from five to ten years to construct.

5. Power Generation

Fuel assemblies are periodically loaded into an LWR. The average assembly stays in the reactor for three to four years, once the plant reaches equilibrium conditions. When the fuel is ready for discharge, the initial enrichment of about 3% U-235 has been reduced to approximately that of natural uranium (.7%). The fuel also contains plutonium and fission products. The latter make spent fuel intensely radioactive.

6. Spent Fuel Storage

After the fuel has been irradiated and can no longer be effectively utilized, it is removed from the core of the nuclear plant and stored for several months in the fuel storage pool at the plant site for cooling. Following cooling and pending the availability of reprocessing capacity, the fuel is either stored on the plant site or moved to an interim storage facility. Concepts for temporary storage include wet and dry methods. The wet method refers to the storage of spent fuel in large pools, as is currently the practice at the reactor site, while the dry method refers to the dry well concept (earthen shield, caisson), and air-cooled vault, or "Stonehenge" concept.⁴ A storage facility capable of supporting 10 power plants is estimated to take 4-10 years to construct.

⁴Both dry and wet storage concepts are being examined in the government's SURFF (Spent Un-Reprocessed Fuel Facility) program being managed by the Rockwell Corporation [27]. These concepts will be evaluated using a matrix of relative merits including cost, technical feasibility, relative risk and use of scarce resources. According to one plan, the initial SURFF facility will be sized to store

7. Spent Fuel Shipment

The movement of discharged fuel from the power plant to an interim storage facility or reprocessing facility requires a shipping container that is capable of providing shielding from the radioactive materials contained within the fuel and adequate cooling from the residual heat produced by the radioactive materials. The container is required to be able to maintain its integrity under severe accident conditions, including a 30-foot drop, immersion in water, and fire. These requirements result in shipping containers weighing, when loaded, upwards of 100 tons.

8. Reprocessing - MOX Fuel Fabrication

Following storage for cooling, the spent fuel can be shipped to a reprocessor to reclaim the residual uranium and plutonium and to concentrate the radioactive fission products⁵. The process consists of: (i) head-end treatment, (ii) separation or extraction, and (iii) product purification. The head-end treatment prepares different types of fuel elements for reprocessing. The practice is to remove the cladding from the fuel either mechanically or chemically and then to dissolve the fuel material in nitric acid.

A number of different methods can be used to extract uranium and plutonium from the fuel solutions⁶. These methods include solvent extraction and continuous ion exchange. The process employed exclusively in the U.S. is the PUREX process. It uses solvent extraction. The product of the extraction step is a nitrate solution of plutonium and uranium. The uranium is recovered as a nitrate (liquid) and can be converted to UF_6 (solid). The plutonium is recovered as a nitrate (liquid) and can be converted to the oxide (solid). The uranium and plutonium recovered can be used as feed material for additional fuel. The separated fission products (high-level waste) from these processes must be solidified

spent fuel from all LWR's through 1990, and will hold 100,000 to 120,000 spent fuel assemblies (equivalent to the 10-year output of 170-200 1-GWe LWRs). Passive storage will be provided by the facility for a minimum of 25 years. In this study, the water pool storage concept is considered (see Chapt. 6, Part B).

⁵No civilian reprocessing of spent fuel is now being carried out in the United States, although three commercial plants have been built. The Allied Gulf Nuclear Services (AGNS) plant in Barnwell, South Carolina, is likely to be the first operational plant in the U. S. given a positive decision on reprocessing. In Europe, France is reprocessing spent fuel from commercial reactors at La Hague. However, the U. S. does reprocess material produced from the military nuclear program at Hanford and Savannah River.

⁶A comprehensive review and comparison of these methods is given in Dr. Guna Selvaduray's doctoral dissertation. The proliferation implications of these methods are compared in his work, along with comparative economics and efficiency [60].

in preparation for its ultimate disposal. A reprocessing facility such as that built at Barnwell, S. Car., is capable of handling the output of 50 1-GWe power plants per year. Construction lead times reflect regulatory conditions, and are estimated to be on the order of 10 to 15 years. A mixed-oxide (MOX) fuel fabrication facility will take plutonium oxide from the reprocessor and mix it with natural or enriched uranium to produce MOX fuel. This fuel will then be shipped to reactors for use.

9. Waste Disposal

Upon separation in the reprocessing facility, radioactive wastes may be solidified into an insoluble, non-leachable form. The solid waste thus produced would be packaged and stored. The long-term approach that has been suggested is to isolate wastes in geologic formations whose stability has been demonstrated over hundreds of thousands of years. The most promising of these formations are bedded salts. After a number of false starts (e.g., Lyons, Kansas), the DOE is currently designing a pilot facility for the storage of wastes in bedded salt formations. Upon satisfactory completion of the pilot plant, it is then planned to construct two large-scale facilities by 1985. Current concepts include the ability to retrieve the wastes should new approaches to waste storage be developed following the initial placement of the wastes [13].

C. Reprocessing and Siting Strategies

Five reprocessing strategies have been proposed [14]:

- (i) prompt reprocessing of spent fuel (after 150-day minimum cooling period), recycling of the recovered uranium, and storage of the plutonium for future use;
- (ii) prompt reprocessing of spent fuel with recycle of both uranium and plutonium in LWRs utilizing an upgraded materials and plant-protection system;
- (iii) prompt reprocessing of spent fuel for recovery and recycling of uranium with storage of plutonium for ultimate disposal;
- (iv) storage of spent fuel for later recovery and recycle of the uranium and plutonium (retrievable storage); and
- (v) storage of spent-fuel for ultimate disposal, also known as the "throw-away" cycle.

If reprocessing is permitted, one of the first three strategies will be followed⁷. Delay implies option (iv) will be followed, while prohibition implies the last option will be taken.

In the past, nuclear facility siting decisions have been made on a case-by-case basis by disparate decision-makers; the utilities and delegated state and federal government agencies decide on the location of power plants, while the nuclear industry and the government decide on the location of fuel-cycle facilities. However, new siting strategies have been suggested that will require consolidation of future decision-making on nuclear facility siting (Table 2.1). These siting strategies include concepts requiring that the fuel-cycle be *vertically integrated* into a fuel park where two or more fuel-cycle facilities would be collocated⁸. *Horizontal integration* schemes, including nuclear center and energy park concepts, have also been suggested where four or more large-scale reactors would be located at one site [28,29]. Capital costs of construction, by far the largest single component of nuclear electricity cost, would be minimized in the nuclear center concept through the use of on-site factory and modular production line construction methods. Combinations of both vertical and horizontal integration have also been suggested.

Another incentive behind co-location schemes is the achievement of economies-of-scale, the concept according to which capital costs will decrease

⁷For the purposes of this study, options (i) and (iii) may be neglected. If reprocessing is permitted, then it is likely that there would be recycle of both recovered uranium and plutonium (strategy (ii)). This assumption is based on several observations:

- it is unlikely that plutonium will be stored for use in breeder reactors in the near term, both for reasons related to safeguards and the commercial timing of the breeder, and
- plutonium is too valuable to be stored for ultimate disposal purposes; in addition, the decision to dispose of plutonium for safeguards reasons would imply prompt disposal.

⁸Motivations behind this concept include decreasing the likelihood that nuclear material can be diverted while in transit between fuel-cycle facilities, and decreasing the capital costs of construction. Sky-rocketing capital costs have led to concepts of standardization of design, and suggestions of ways to decrease construction lead times.

Table 2.1

PROPOSED NUCLEAR FACILITY SITING STRATEGIES*

<u>Strategy</u>	<u>Description</u>
1. Dispersed Siting (Traditional)	Does not consider interaction of various facilities as prime objective. Considers individual facility type and optimizes with respect to that particular facility.
2. Fuel Park (Vertical Integration)	Co-location of two or more fuel-cycle facilities. Avoids transportation, handling, and operating expenses of transporting fuel from plant to plant. Also, probability of plutonium theft is minimized.
3. Nuclear Centers (Horizontal Integration)	Co-location of four or more reactors, either of similar type or a combination of types. Concept here to minimize capital costs through the use of on-site factory and modular production-line construction.
4. Off-Shore Dispersed Siting	Has been advanced as siting concept for nuclear power plants. Advantage is to keep transmission costs to minimum in regions where it is otherwise infeasible to site plants near population center.

* Concepts which combine one or more of the four alternatives described here have also been suggested as possible siting strategies.

on a per-unit basis as the size of a plant increases⁹. However, disagreement exists on whether or not larger power plants are more reliable than smaller plants [30]. If less reliable, the assumption that economies-of-scale obtain is not a valid one. Because of the sparse historical data base on reactor operating reliability as a function of unit size, it is difficult to reach a definite conclusion on the validity of the economy-of-scale concept applied to nuclear reactors at this time [31].

⁹The implications of such a relationship have been examined by Marchetti, who has suggested the construction of nuclear islands, each with its own 1 TkwT power plant composed of five 200 Gwt reactors. Supporting fuel cycle facilities would be co-located with the plant on barges docked in the island harbor. The high-level waste produced would be discharged in the deepest recesses of the island core. Because of the large capital savings, Marchetti suggests that uranium extraction from sea water would become economical, providing a seemingly endless source of nuclear fuel. Energy would be transported in the form of hydrogen to population centers, where the hydrogen would be used to fuel electric generators and other devices, such as automobiles [32].

Chapter 3

MAJOR UNCERTAINTIES AND UNRESOLVED ISSUES

Our passions, our prejudices and dominating opinions, by exaggerating the probabilities which are favorable to them and by attenuating the contrary probabilities, are the abundant source of dangerous illusions.

--Laplace

A Philosophical Essay on
Probabilities

Overview

This chapter focuses on the major uncertainties that affect re-processing benefits (Table 3.1). For each key uncertainty, the current literature (as of 1978) has been consulted to establish value ranges over which the author has assigned her personal prior distributions (called simply "priors").¹ Placing the data into probabilistic terms reflects today's uncertain *state-of-information* that is characterized by expert disagreement on the future resolution of these uncertainties. By describing the information probabilistically, arguments can be reduced from those that moralistically debate the "rightness of alternatives" to those that technically evaluate the likelihood-of-event occurrence.² The unresolved issue of private and social discount rates is also discussed in this chapter.

¹Alternatively, experts could be consulted and interviewed directly to arrive at consensus distributions that would more adequately reflect today's state-of-information regarding these uncertainties (see references on the science of probability encoding [33]). Even with this approach, it is difficult to avoid subjective judgments and inherent biases.

²For example, debates over energy demand often focus on the social consequences a demand level is thought to imply rather than on those factors that actually determine that demand level (for an opinion on how demand levels are thought to imply different social and technical consequences, see Lovins' description of the hard versus soft path[34]).

Table 3.1

KEY UNCERTAINTIES RELATED TO THE REPROCESSING DECISION

- A. Electricity Demand: i. Growth Rate, ii. Nuclear Supply
 - B. Uranium Resources: i. Availability, ii. Rate of Discovery, Recovery and Cost, iii. Foreign Sources
 - C. Enrichment: i. Availability, ii. Cost, iii. Alternative Technologies (Centrifuge, Laser, etc)
 - D. Reprocessing: i. Cost, ii. Commercial Introduction Date, iii. Market Demand
 - E. Breeder: i. Cost Differential Between LMFBR and Alternative Technologies, ii. Introduction Date, iii. Growth Rate
-

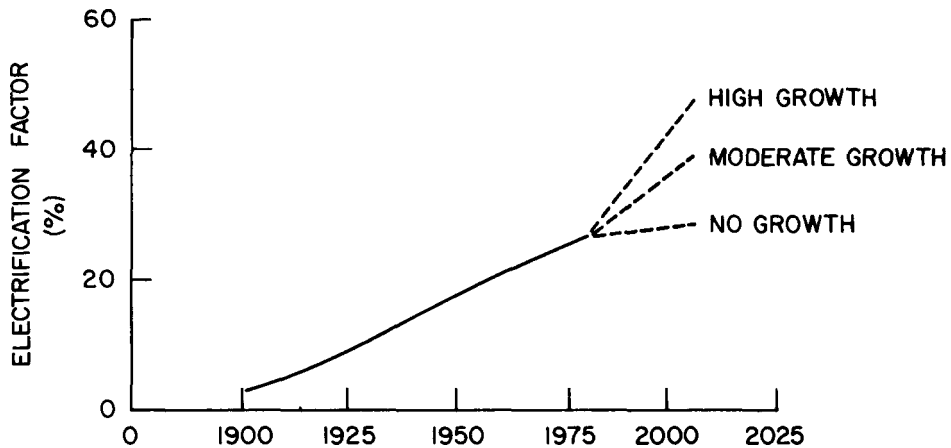
A. Electricity Demand and Nuclear Supply

Future total energy demand is uncertain, but can be bounded by forecasts [35-40]. Forecasting techniques vary from simple judgmental methods to sophisticated mathematical models. A popular method is to extrapolate historical demand trends based on some set of economic growth and technological progress assumptions. Electricity demand is conditional upon total energy demand, and is usually projected as a percentage of total demand.³ Historical trends indicate how the percentage of primary energy converted to electricity has increased over time (Fig. 3.1). Whether or not this trend toward increased electrification will continue at historical rates is debated; Weinberg [35] and the Edison Electric Institute [36] expect that the percentage will increase to 50% by the year 2000 from its present value of 28%, while the Ford FFEPP study expects stabilization at 31% [37]. The range of values used in this study is 4-6 TkwH in the year 2000.

Nuclear supply forecasts have varied widely over the past fourteen years. However, over the next ten years, maximum capacity is relatively certain as additional capacity has already been built, designed, or contracted for. Thereafter, a wide range of forecasts is justified (Table 3.2). Low forecasts (240 GWe in 2000) could become

³A comprehensive treatment of long-range econometric models used to forecast electricity demand is given by Hieronymus et al. [38].

Figure 3.1 Historical Electricity Growth as a Percentage of Total Primary Energy



reality or be too high if a nuclear moratorium takes place, while high forecasts (720 GWe) will occur only if nuclear power is vigorously pursued as a concerted national policy.⁴

B. Uranium Cost and Supply Availability

The value of recycled fuel is a function of uranium cost. In turn, uranium cost is dependent upon the grade and availability of ore; costs are low if high-grade ore is abundant, while scarcity implies high cost. Forecasts rely on supply and demand, resource level, and discovery-production rate estimates. A production rate ("producibility") indicates how quickly uranium can be placed on the market and, combined with resource estimates, determines commercial supply availability. Production rates are governed by capital and labor availability and economic-institutional bounds on the domestic uranium industry.

Current resource estimates are based on past exploration efforts. In 1973, the government initiated the National Uranium Resource Evaluation (NURE) program to update, by the early 1980's existing estimates of resources below the 50 \$/lb-U₃O₈ limit. This limit was chosen because

⁴Nuclear power could contribute to total energy demand if used to produce hydrogen [41]. However, the hydrogen economy is not a likely near term alternative. Therefore, in this study, nuclear supply is considered to contribute only to electricity demand satisfaction.

Table 3.2
 NUCLEAR LWR SUPPLY SCENARIOS (1975-2005)*

Scenario	Annual Growth Rate**	Growth Description	GWe Installed Nuclear Generating Capacity						
			1975	1980	1985	1990	1995	2000	2005
A	2%	Very Low	40	76	88	97	107	120	130
B	8-5%	Low	40	76	110	162	188	240	306
C	15-9-3%	Modest	40	76	155	200	280	360	420
D	20-8-3.5%	Moderate	40	76	155	200	350	480	540
E	3.0-10-5%	Moderately High	40	76	155	220	450	600	660
F	22-15-8%	High	40	76	180	260	500	720	840
G	25-18-10%	Very High	40	76	180	300	560	840	950

* Scenario C reflects the current Carter administration projections (as of 1978). Scenarios E-G are growth scenarios which are included to indicate the capability of an LWR-based nuclear economy given a decision was made in the near future to expand nuclear capacity, an event assumed very unlikely to occur.

** These growth rates are higher initially to reflect concave nature of LWR capacity supply curve.

very little information about resources above the 30 \$/lb-U₃O₈ limit is currently available. Less than 10% of all potential resource regions have been completely explored, leading some to feel that the government's current estimates are too low [42]. Searl, for example, has published higher estimates, based on a \$100/lb limit, that are considerably more optimistic [43].⁵

Domestic resource estimates from three recent studies indicate the degree of uncertainty present in judging future economic uranium supply (Table 3.3). High estimates are based on the optimistic view that the NURE study will be successful in locating new domestic resources. Even given the outcome of an optimistic NURE finding, disagreement still exists among experts on the subject of "producibility." However, most experts seem to agree that the problem of scarcity is really an economic one that depends most on the expansion rate of the United States uranium mining and milling industry.⁶ The disagreement centers on how fast, and at what price, the industry can expand to meet rising demand. "Producibility" has been estimated by the government; a level of 60,000 tons/year is projected for the 1990's based on currently estimated uranium resources [44]. Attainment of this growth will require substantial construction of new mines and mills, and a continued high level of exploration; a series of events that remains uncertain.

Uranium resource estimates used in this study are those put forth by the Department of Energy (formerly ERDA); an optimistic outcome of NURE

⁵However, Searl's estimates are considered by many experts to be overly optimistic. Criticism of Searl's approach has been directed at: (i) his treatment of depth (which assumes that material is distributed in sandstone with equal frequency throughout the first 4,000 feet), (ii) the concept that total discoveries to date can be treated as a single "district," and (iii) the "block-by-block" idea, derived from mature resources like oil and gas but applied in this instance to uranium, an immature industry [6].

⁶For example, the NEPS study concludes that: "it is not the lack [or abundance] of resources that gives rise to [the fear of shortages], but rather a lack of incentives for exploration and development." However, they take the optimistic view that resources can be developed to supply fuel for LWRs, up to and beyond the end of the century, at costs that will not exceed by much the spot prices uranium sold at during 1976 (the \$40 range) (p. 94, [6]).

Table 3.3

DOMESTIC URANIUM RESOURCE ESTIMATES (U.S.A.)
 (35 \$/lb cutoff; millions of tons recoverable U₃O₈)

1. Department of Energy (ERDA) -- Patterson [44]

Reserves	.64
Probable Potential	1.06
<hr/>	
Best Estimate	1.7
Possible Speculative	1.8
<hr/>	
High Estimate	3.5

2. CONAES Uranium Resource Group -- Cazalet/Hogan et al. [45]*

	Low Estimate	Best Estimate	High Estimate
Reserves	.480	.640	.640
By-product	.020	.060	.140
Potential Resources (all categories)	.500	1.060	3.000
Sum (total resources)	1.000	1.760	3.780

3. Ford NEPS -- from Table 2-5 [6]**

Reserves	.64
Limited Potential	1.06
<hr/>	
	1.70
Full Potential	2.92
<hr/>	
Reserves and Full Potential	3.56

* Committee on Nuclear and Alternative Energy Sources (CONAES).

** The Ford NEPS group did not explicitly make judgmental low, best, or high estimates of uranium resource or commercial availability. However, implicit judgments are evident in their conclusions (see text).

is taken to imply the realization of the "high" estimate (3.78 million tons U_3O_8 at 35 \$/lb U_3O_8), while a pessimistic outcome is taken to imply the realization of the "best estimate (1.76 million tons U_3O_8 at 35 \$/lb U_3O_8) [44]. Cost estimates used range from 35-100 \$/lb U_3O_8 . Resource estimates for uranium available above the 35 \$/lb U_3O_8 limit reflect a range of uranium supply curves the likelihood of which depends on the optimistic-pessimistic outcome of the NURE study.

C. Enrichment Cost and Capacity Availability

Enrichment requirements depend upon uranium demand, recycled fuel flows, construction lead times, tails assay selection, and power plant capacity factors.⁷ Reprocessing, followed by recycling of plutonium, could decrease uranium demand by factors of 20-30%, thereby reducing enrichment requirements. The tails assay selected affects uranium demand and enrichment capacity; tails assay is currently set at the .2% level, which is optimal at current uranium and power cost conditions [44]. In the future, as costs change, the tails assay optimization will also change reflecting the new conditions. In theory, there is an optimum tails assay for any given pair of natural uranium and enrichment energy (SWU) costs. However, political considerations (e.g., need to meet foreign commitments) can override the theory. Power plant capacity factors also affect fuel demands but are themselves uncertain since power plant operating data are only now beginning to accumulate in a statistically meaningful way.⁸

Enrichment capacity projections are provided by the U. S. government as the only domestic enriched uranium supplier.⁹ The United States has committed its future supply to foreign as well as domestic customers through the 1980's, with almost 40% of the capacity expected to support foreign demand [46]. The government plans to expand its Portsmouth capacity by

⁷It is projected that the U.S. will need new enrichment capacity at a rate of ~2 million SWU/year from the mid-1980's onward, for a 500 GW(e) supply of nuclear capacity in the year 2000. This corresponds to the installation of a 9 million SWU/year diffusion plant every four years [46].

⁸Current operating experience (as of 1976) indicates that LWRs operate with ~61% average capacity factor. Observers expect the average to climb to 69% by the early 1980's reflecting improvements [31].

⁹The government operates three installations nationwide; in Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio.

Table 3.4

BASE-LOAD GENERATION TECHNOLOGIES POTENTIALLY AVAILABLE FOR U.S. COMMERCIAL DEVELOPMENT

Technology Category	Nuclear	Fossil Fuel	Solar	Geothermal	Hydro
Earliest Commercial Introduction					
Currently Operational or Under Construction	Light-Water Reactor (LWR) High-Temperature Gas Reactor (HTGR)	Conventional Coal/Steam with Flue Gas Desulfurization (FGD) Oil (or Gas) Fired Steam			Hydroelectric Hydrothermal (Vapor-Dominated)
1980 - 1989		Atmospheric Fluidized Bed Coal/Steam (AFB) Fuel Cell/Integrated Coal Gasifier Conventional Coal With Advanced Scrubbers Open Cycle Gas Turbine Combined Cycle, With Integrated Coal Gasifier		Geopressurized	Hydrothermal (Liquid-Dominated)
1990 - 1999	Liquid Metal Fast Breeder Reactor (LMFBR)	Open Cycle MHD (Coal Fired) Pressurized Fluidized Bed (Coal/Steam) Closed Cycle Gas Turbine With AFB (Coal) Metal Vapor Topping Cycle With Steam Bottom Cycle (AFB/Coal)	Ocean Thermal (OTEC) Power Towers; Windmills	Hot Dry Rock	
Post 2000	Fission/Fusion Hybrid Reactor Fusion Reactors Alternative Fast Breeders & Converter Reactor Systems & Fuel-Cycles		Solar Satellite Solar Thermal or Photovoltaic With Storage		

1985 or 1990 to meet demands. Further, in the future, a portion of domestic supply may be provided by foreign industrial concerns (e.g., URENCO) that are now active in the development and commercialization of enrichment technologies. Enrichment cost estimates used range from 75-125 \$/kg-SWU (1975 dollar terms) as projected by the government [15,47].

D. Reprocessing Cost

No commercial reprocessors are currently operating in the United States (as of 1978). Unit cost estimates must be made without the benefit of on-line experience. Estimates range from a low of 30 \$/kg-heavy metal (HM) to above 350 \$/kg-HM (1975 dollars). Three operations are included in most estimates: (i) fuel receipt and storage, (ii) PUREX-based reprocessing of spent fuel, and (iii) conversion of the uranium, plutonium, and waste products into suitable chemical forms. Allied Gulf Nuclear Services (AGNS) has constructed a facility to carry out each of these operations, but their cost estimate of \$178/kg-HM reflects past conditions and is useful only to set a lower bound on future costs [13]. Estimates used in this study range from 150-350 \$/kg-HM (1975 dollar terms). Higher estimates' effects are also examined (up to 500 \$/kg-HM; see Appendix B.3.3).

E. Cost Differentials Between Alternative Technologies

A new electricity generating technology will be commercialized only after demonstrating a competitive cost-per-kWh. Although adoption is not entirely motivated by cost savings, it is the single most important objective. In this section, alternative base-load generation technologies are compared to nuclear power on a levelized cost-per-basis.¹⁰ Base-load generation technologies available for potential future development can be categorized as a function of their earliest

¹⁰A base-load plant is nominally designed to operate 24 hours per day, but a plant is generally considered to be base-load if it operates more than 5,000 hours per year, corresponding to a 57% capacity factor. Peak-load generation refers to periods of peak demand, generally averaging four hours or less per day.

Table 3.5

ESTIMATES ON POWER COSTS (MINUS FUEL COSTS)
 FOR ALTERNATIVE BASE-LOAD TECHNOLOGIES (in 1975 \$) [48,49]^{a/}

Technology	Unit Costs (mills/kWh)			
	Range on Capital Costs (\$/kW)	Levelized Capital Costs ^{b/}	O & M	Total
1. LWR	500-700	12.7-17.8	1.3	14-19.1
2. Conventional Coal	400-550	10.2-14.0	2.6	12.8-16.6
3. Oil and Gas (SWT)	320-440	8.1-11.2	2.3	10.4-13.5
4. Advanced Coal Technology (ACT)	373-686	9.4-17.4	2-3.3	11.4-20.7
5. LMFBR	750-1400	19.0-37.4	1.5-2.0	20.5-39.4
6. Advanced Energy Technology (AET)	1191-1841	30.2-55.6	3.0	33.2-58.6

^{a/} Estimates are based on assumption that capital costs for power plants escalate no faster than the general inflation rate (see text). Estimates include interest during construction.

^{b/} Capital costs are based on a 13%/year pretax cost of capital, 30-year service life, and 60% capacity factor over the life of the plant. Therefore,

$$\text{levelized } \frac{\text{mills}}{\text{kWh}} = A[\text{CAP COST} \div \text{CF} \times 8.76 \times 10^3 \text{ hrs/yr}]$$

$$\text{where } A = [i(1+i)^L] / [(1+i)^L - 1]$$

and i = pretax cost of capital, L = lifetime of the plant, CF = capacity factor, CAP COST = capital cost, or

$$\text{levelized } \frac{\text{mills}}{\text{kWh}} = .0254 \times \text{CAP COST}$$

commercial introduction date (Table 3.4).¹¹ In this analysis, it has been convenient to define an Advanced Energy Technology (AET) that includes all non-LMFBR related futuristic alternatives, including fusion, central station solar, and advanced converter reactor-fuel cycle systems. Advanced Coal Technologies (ACT) are grouped together, and a Swing Technology (SWT) based on oil- and gas-fired base-load plants is also defined. Power costs (minus fuel costs) can also be estimated for each of the alternatives (Table 3.5).¹²

Over the past few years, fuel costs have risen faster than general inflation, but it is not certain whether or not these trends will continue.¹³ Fuel costs examined are those for uranium, coal, and oil. Nuclear fuel costs can be estimated on the basis of expected fuel-cycle

¹¹It is unlikely that all technologies listed will be applied within the indicated time-frame, or even that all of them will ever be developed for commercial use. Many of the fossil fuel alternatives are coal technologies that are, to some extent, in competition among themselves. An example of competing technologies are the magnetohydrodynamic (MHD) generators and high-temperature gas turbines, both promising to increase thermal efficiencies to 40-60%. Although the possibility exists that both will be adopted, it appears that the alternative first demonstrated successfully will have the competitive advantage.

¹²Capital costs are assumed to grow no faster than inflation. Although this has not been the case for the last 5 to 10 years, during which the cost per kWh has escalated at 13% per year for nuclear plants and 8% for fossil plants (compared to a general inflation rate of 6½%), it is assumed that a significant difference in real escalation rates cannot be sustained over this period [48]. That is, construction times have increased by about 2 years during the last 5 years, and the extra interest during this period has been the major contributor to cost increases, accounting for nearly half of the current capital costs of nuclear plants (as of 1978). Construction time increases are due primarily to regulatory changes, although in some cases, extensions have been deliberate reactions to a slowdown in demand growth. Extrapolating these trends to 2000 would result in construction times of 20 or more years, thought to be a fairly improbable event. Thus, an extrapolation of the cost trend over the last 5 years would produce an upper limit on these costs, with the lower limit set by costs growing with the general inflation rate.

¹³A range of fuel cost projections are important to establish since fuel costs affect the relative attractiveness of technologies.

Table 3.6

NUCLEAR FUEL CYCLE UNIT COST ESTIMATES^{a/}
(mills/kWh; 1975 \$)

	LWR								FBR Early Oxide
	No Pu Recycle				With Pu Recycle				
Tails Assay (%)	.2				.2		.3		
Uranium Feed (ST/year)	151		187		117		144		0
Enrichment (10 ³ kgSWU/yr)	113		91		89		72		0
	LO	HI	LO	HI	LO	HI	LO	HI	-
Uranium Feed (mills/kWh)	1.38-4.6		1.71-5.70		1.07-3.57		1.32-4.40		0
Enrichment (mills/kWh)	1.29-2.15		1.04-1.73		1.02-1.70		0.82-1.37		0
Fab., reprocessing, and HLW/Spent Fuel Storage ^{b/} (mills/kWh)	.75-1.75		.75-1.75		1.10-2.20		1.10-2.20		1.5-3.5 ^{c/}
Total Fuel Cost (mills/kWh) ^{d/}	3.42-8.5		3.5-9.18		3.19-7.47		3.24-7.97		1.5-3.5

^{a/} Calculations independent of capacity factor; based on fuel cycle unit cost estimates in [47]; e.g., uranium at 35-100 \$/lb U₃O₈.

^{b/} Using mass balance factors of .045 x Output of Reprocessor = Input to HLW storage, .096 x MT U₃O₈ = Input to Fabricator.

^{c/} Assumes that breeder fuel will be more expensive to reprocess than LWR fuel.

^{d/} Excludes capital charges on initial fuel inventory.

operating conditions (Table 3.6).¹⁴

Coal resources are plentiful in the United States. Estimates indicate a total resource base of ~4000 billion tons, with low sulfur ($\leq 1\%$ by weight) representing roughly 30% of the total. Coal costs are a function of ore grade, heat and sulfur content, and the mine type (surface or underground). Costs also reflect demand trends.¹⁵ In the United States, coal is found in both the east and the west. Eastern coal is high in sulfur content and occurs in deep underground deposits, while western coal is relatively low in sulfur and can be surface mined. Recent estimates of western supply assume that strippable coal can be removed at costs of \$4.50-\$8.50 per ton, and that supply is price-elastic in that range [50]; eastern supply is far less price-elastic. Eastern low-sulfur coal is about four times as expensive to extract as western, low-sulfur coal, and will most likely be used only in those areas where it has large transportation cost advantages. High or medium sulfur coal may sell at a discount from low sulfur coal approaching the cost of cleaning and scrubbing required for environmental regulation compliance.

Electrical generating fuel costs for coal as a function of type and control mechanism are estimated as 6-15 mills/kWh [50,51]. Whether or not the lower coal prices will obtain depends on how much western coal production

¹⁴A more detailed treatment of nuclear fuel cycle logistics is given in Chapter 4.

¹⁵The average price per ton dropped from \$5.00 in 1948 to \$4.39 in 1963. Then, as electric utility and export demand for coal increased in the 1964-70 period, the price rose to \$6.26. It continued to rise gradually during the early 1970's. In 1974, however, the average price surged to \$15.75 per ton, almost twice that of the previous year, and to \$18.75 in 1975. Three reasons were given for the sudden increase: (i) Arab oil embargo of September, 1973, (ii) the United Mine Workers contract was about to expire and fears of a strike led to coal consumers stockpiling, and (iii) the end of price controls during August, 1973, and March, 1974. These higher prices paid by utilities are known as "spot" prices, reflecting immediate or near-term delivery paid under adverse conditions. Most purchases now negotiated by utilities are long-term 20-to-30 year contracts predicated upon a base price at the mine. Added to the base price are production escalators that vary with changes in the costs of mining [50].

Table 3.7

PRICE RANGE ON PRIMARY FUEL FOR 1975-2010 BASED ON CONAES-
MODELING RESOURCES GROUP LONG-RUN MODEL RESULTS (1975 \$/MMBTU) [53]

		Oil ^{a/} (\$/bbl)		Coal ^{b/} (\$/ton)		Uranium ^{c/} (\$/lb U ₃ O ₈)	
1975	Actual	1.5	(9)	0.75	(15)	0.17	(30)
1990	Low	2.4	(14.39)	0.75	(15)	0.17	(30)
	Base	2.43	(14.56)	0.89	(17.8)	0.18	(32)
	High	2.71	(16.24)	1.38	(27.6)	0.23	(39.9)
2000	L	2.66	(15.95)	0.75	(15)	0.17	(30)
	B	2.89	(17.35)	0.89	(17.8)	0.19	(33.6)
	H	3.60	(21.59)	1.5	(30)	0.27	(47.7)
2010	L	2.82	(16.89)	0.75	(15)	0.17	(30)
	B	3.58	(21.5)	0.89	(17.8)	0.21	(36.5)
	H	4.88	(29.25)	2.72	(36.3)	0.35	(61.7)

^{a/} Assumes 6 MMBTU/bbl total average cost of synthetic fuels delivered as 3.70 \$/MMBTU.

^{b/} For coal, to convert \$/10⁶ Btu to \$/ton, multiply by 2000 lb/ton x heat value of the coal in Btu/lb. Typical heat values range from 10-15,000 Btu/lb. Examples are Wyoming strip coal at 10,500 Btu/lb and Illinois deep mined coal at 12,560 Btu/lb.

^{c/} Assumes 178 MMBTU/lb U₃O₈. This factor was derived as follows: In 1 lb U₃O₈, there are $3 \cdot 238 / (3 \cdot 238 + 8 \cdot 16) = 714 / 842 = .848$ lb natural uranium. Uranium-235 is .7% of natural uranium, or there is .0059 lb U-235 in 1 lb U₃O₈. There are thus 2.69 gm of U-235 per lb U₃O₈. In a thermal reactor, 1.24 gm U-235 is consumed to produce 1 Mwt-day, or 24 Mwt-hours (from Lamarsh [54]). Since 1 kWh = 3413 Btu, 2.69 gms of U-235 could produce at very maximum $(2.69 / 1.24) \times 8.19 \times 10^7$ Btu, or 178 MMBTU/lb U₃O₈.

increases.¹⁶ Production rates are very uncertain; observers hold opposing views on coal producer's ability to keep up with demand.¹⁷ Many agree that coal can meet a substantial portion of demand, but that coal shortages become more likely if coal is forced to meet all of future demand.

In the near term, coal and nuclear supply shortages may make the use of oil necessary as a "swing fuel."¹⁸ Forecasting oil price is difficult because world oil supply is controlled by an international cartel (OPEC) whose behavior is unpredictable.¹⁹ Domestic forecasts are further complicated by complex regulations set by the government. Oil price estimates used in this study are compared with those for coal and uranium on a dollar per million BTU basis (Table 3.7).

¹⁶Although western coal is projected to be a major source of supply, the extent of its movement east will depend on the resolution of questions regarding: (i) Clean Air Act regulations, implementation, and enforcement, (ii) environmental regulations, (iii) taxes, and (iv) transportation costs. Serious economic problems in expanding western production from a little more than 100 million tons/year in 1975 to 300-400 million tons/year in 1985 could develop. Supply bottlenecks in transportation equipment (railway/truck) are possible given the high rate of expansion.

¹⁷Modellers place upper bounds on coal's contribution to electrical supply; ranges of between 40 to 50% have been reported [53].

¹⁸Exxon Corporation describes oil as: "the nation's swing fuel. . . the most versatile energy source; only oil is capable of taking up the slack created by the short fall of any other fuel. . . slow growth in coal or nuclear supply will rapidly translate into additional oil imports." [55]

¹⁹Attempts to forecast the world price of oil by modeling OPEC behavior have been made by a number of economists [56]. Future oil prices are also affected by the outcome of the outer continental shelf explorations, by the success of enhanced recovery techniques, and by how responsive oil price is to decreased demand resulting from conservation and substitution effects. Oil price is upper-bounded by synthetic and shale oil costs, given these technologies may be developed without additional environmental constraints.

F. Private and Social Discount Rates

Two discount rates²⁰ are significant in energy-economics calculations: the rates-of-return on private capital and the social discount rate (SDR). Cost of capital is reflected in the pre-tax rate *producers* use to discount profits from investment projects in the relative short term; it is used to convert construction capital costs per kw into annualized power-generation costs per kWh in energy studies. The SDR discounts benefits current *consumers* derive from future consumption of others over a longer term; it measures the value society places on the receipt of future benefits.²¹

The task of selecting an appropriate value for the SDR is difficult. Two approaches have been taken in the economic literature: (i) the welfare function approach based on social preferences [57], and (ii) the opportunity cost approach [58,59]. Using the welfare function approach, Dorfman has estimated the SDR applicable to consumption to be no greater than 3%, with a growth component due to inflation of 4.5%. Based on the opportunity cost approach, the CONAES Modeling Resources Group used a post-tax rate-of-return of 6% to discount social benefits, measured in constant dollars [53].

Compared with current practice in governmental project evaluation and similar enterprises, these estimates are low. The Department of the Interior, for example, commonly uses 8% for internal purposes. The Office of Management and Budget specifies a 10% rate of discount for projects to be included in budgetary requests except for water resource

²⁰Discount rates are the interest rates used in present worth calculations; the present worth of a series of future payments is defined to be the investment necessary to secure the promise of future payments. If different series of payments are equivalent to the same present worth, the series are defined to be economically equivalent.

²¹A non-zero factor implies society favors near-term over future consumption; the larger the SDR, the greater value society places on present consumption (alternatively, the more myopic society tends to be, reflecting a "consume now, pay later" attitude).

projects, which are tied by act of Congress to use the yield of long-term government securities.

Thus, a range of between 3-10% for the social discount rate is suggested both by economic theorists (at the low end) and actual governmental practice (at the high end). Private market rates vary from between 10-15% depending on the analyst or organization involved. Nominal values used here to discount cost-benefits measured in constant 1975 dollars are 6% for the SDR and 13% for the private market rate. (These rates are identical to the values adopted by the CONAES Modeling Resources Group [53]).

Chapter 4

DIRECT ECONOMIC BENEFITS DUE TO THE REPROCESSING OF LWR FUEL AND RECYCLE OF RECOVERED PRODUCTS

One of man's principal decision-making spheres is the economic one. Economic outcomes are measured in monetary terms, and the result of an investment may be described as a time stream of dollars. These cash flows are uncertain, the uncertainties resolving over time. In essence then, an investment is a stochastic process, or *dynamic lottery*.

--Pollard [61]

Overview

This chapter assesses differences in LWR fuel cycle costs implied by competing reprocessing decision options. Translated into direct economic benefits, the differences indicate the effect the reprocessing of spent fuel and the recycling of recovered products may have on nuclear electrical generating costs.

A. Extended Decision Model

The reprocessing decision model of Chapter 1 can be extended to reflect possible United States reprocessing industrial futures (Figure 4.1). As of 1978, the government must decide whether to permit, delay, or prohibit reprocessing. A prohibit decision implies that the nuclear fuel cycle will evolve in an open cycle mode, while a decision to permit reprocessing implies that the industry can begin operation as soon as reprocessing capacity is made commercially available. After beginning operation, the reprocessing industry will decide, say in 1985, whether or not to expand or to shut down because of technical or commercial failure. A delayed reprocessing decision implies that the government must face the same decision at a later time while the fuel cycle continues operation in an open cycle mode. For the sake of visual simplicity, the effects of key uncertainties on the number of available expansion paths is described in terms of an "extended branch" notation. Dates of resolution on key uncertainties are defined as shown (Table 4.1).

Figure 4.1 Extended Decision Tree for the U.S. Reprocessing Decision

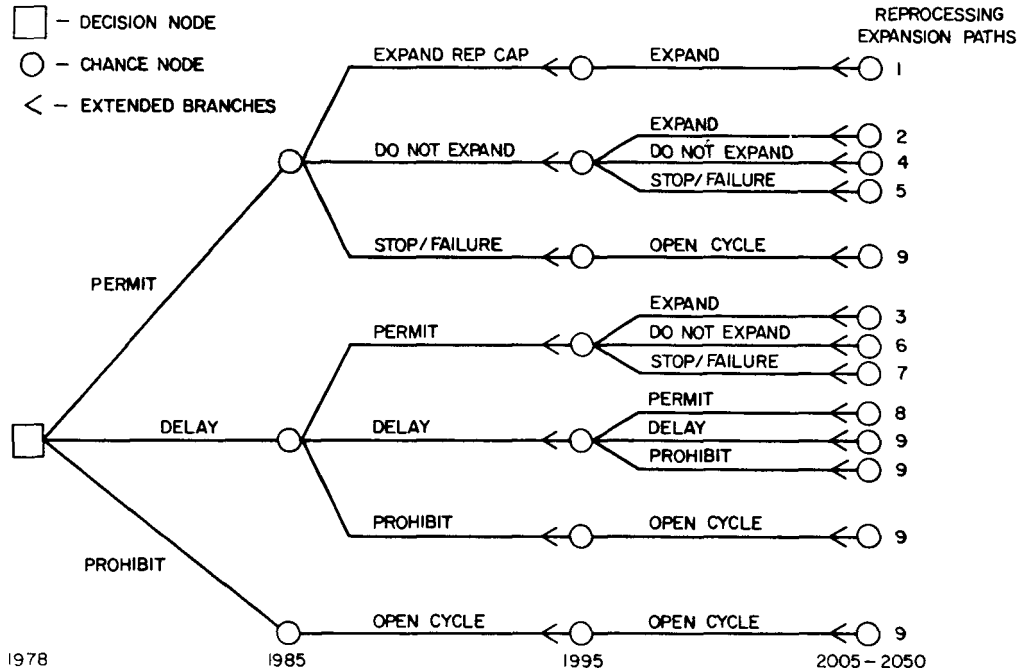
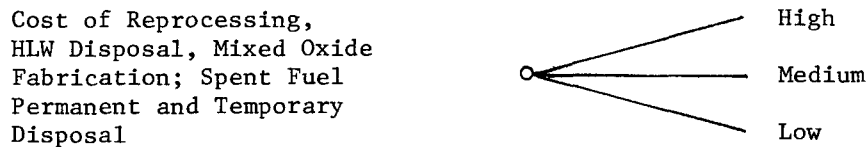


Table 4.1
DATES OF RESOLUTION OF KEY UNCERTAINTIES

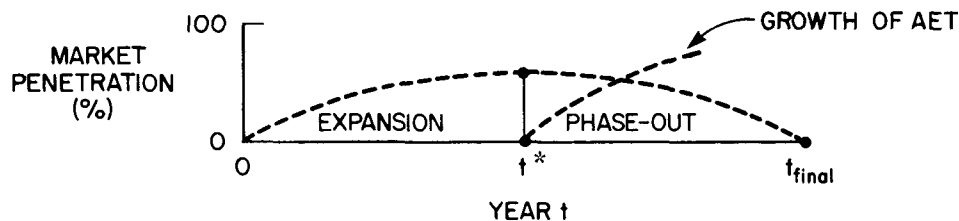
	1985	1995	2005
NURE	<ul style="list-style-type: none"> Optimistic Pessimistic 	Uranium Supply <ul style="list-style-type: none"> High Low 	LMFBR Date-of-Introduction <ul style="list-style-type: none"> 2005 Later
Total Electricity Demand	<ul style="list-style-type: none"> Low Medium High 	Uranium Cost <ul style="list-style-type: none"> High Low 	AET Date-of-Introduction <ul style="list-style-type: none"> 2005 Later
Nuclear Supply	<ul style="list-style-type: none"> Low High 		

Determined at Date of First Commercialization:



To assess reprocessing direct economic benefits, a systems approach based on the decision analysis cycle described in Chapter 1 has been followed (see Appendix B, Figure B.1). In the deterministic phase, a dynamic fuel cycle simulation model is used to calculate total fuel cycle costs of different reprocessing expansion paths. The simulation model follows the expansion period of the LWR industry over the time horizon 1978-2050 (Figure 4.2). During this period, at time t^* , an Alternative Energy Technology (AET) is assumed introduced that gradually replaces LWRs by the year t_f .¹

Figure 4.2 Evolution of the LWR Nuclear Industry



In the probabilistic phase, the uncertainties surrounding key parameters are modeled as discrete lotteries, each branch of which describes a future economic state. The fuel cycle costs calculated in the deterministic phase are interpreted as outcome values associated with these future economic states. The extended decision tree is then "folded back" to arrive at expected value benefits for the permit, delay and prohibit decision options. Finally, a stochastic sensitivity analysis is conducted to indicate the effect changes in the state-of-information on key uncertainties

¹The AET refers to alternative energy technologies for base-load electrical generation, such as fusion reactors, centralized solar plants, etc. (see Chapter 3.E). Substitution is assumed to occur when the AET becomes commercially competitive with the LWR as the result of technological advances, fuel supply constraints, or other considerations. Post-2005 benefits are dependent on the introduction date and growth rate of the AET. Assumptions made on AET introduction date and growth rate are found in Appendix B.3.2.

Table 4.2

METALLIC URANIUM FLOW TO REACTORS (OPEN-CYCLE)

Nuclear Supply Scenario (GWe, 2000)	Integrated Capacity ^{a/} (GWe-years)		Total Energy Out (TkwH) ^{b/}		Fission Thermal Energy (10 ⁹ MWdt)		Fuel Flow to Reactor (10 ³ MTU)	
	1975-2005	2005-2050	1975-2005	2005-2050	1975-2005	2995-2050	1975-2005	2005-2050
A (120)	2770	3760	14.6	19.7	1.84	2.48	59.5	80.3
B (240)	4386	6649	23.1	35.1	2.92	4.44	94.5	143.6
C (360)	5975	9075	31.5	47.9	3.98	6.05	128.8	195.8
D (480)	7045	10955	37.1	57.9	4.68	7.30	151.5	236.3
E (600)	8305	13176	43.8	69.6	5.53	8.80	179.0	284.6
F (720)	9720	15941	51.2	84.0	6.46	10.60	209.1	342.9
G (840)	10930	17068	57.6	94.5	7.27	11.92	235.5	385.9

^{a/} Expected value capacity for years 2005-2050 as a function of pre-2005 supply scenario (see Appendix B).

^{b/} Capacity factor used: CF=60% .

have on the direct benefit calculations.

B. Deterministic Phase: Scenario-Dependent Benefits

The fuel cycle simulation model describes the fuel flow between nuclear facilities. Among the parameters that affect fuel flow are: (i) reactor burn-up (β), (ii) enrichment concentration and tails assay, and (iii) facility efficiency factors. Technological advances also affect fuel cycle flow, as does the recycle of recovered products. For the reactor, uranium ore and fabricated fuel requirements depend upon the burn-up lifetime value (β) achieved by the fuel. A target value is 33,000 MWdt/MTU.² The uranium flow to the reactor is governed by the following relations [62]:

- o Electrical Energy Out (kWh/y) = Capacity (kWe) x d/y x h/d x CF;
CF= 60% (Capacity Factor)
- o Fission Thermal Energy (MWdt/y)= (Total Electrical Energy Out, kWh/y)/
($\epsilon \times 24 \text{ h/d} \times 10^3 \text{ kW/MW}$)
where ϵ is the thermal efficiency ($\epsilon \approx .33$ [63]).
- o Uranium Flow to Reactor (MTU/y) = (MWdt/y)/(Burn-up, β (MWdt/MTU))

For the nuclear supply scenarios described in Chapter 3 and Appendix B, the metallic uranium requirements can be calculated (Table 4.2)³.

In the enrichment stage, changes in the tails assay and percent isotopic concentration of the product stream are exogenous variables set by the operator. Tails assay concentrations of .2-.3% and enrichments of 3-3.5% are chosen as representative of present and future conditions.

²This value is somewhat higher than that achieved in practice; irradiation levels of 27,500 MWdt/MTU for Boiling Water Reactors (BWRs) and 32,600 MWdt/MTU for Pressurized Water Reactors (PWRs) have been reported for reactors operating on reload cores; initial cores are reported at 17,500 MWdt/MTU for BWRs and 22,600 MWdt/MTU for PWRs [63]. A nominal value of 30,900 MWdt/MTU has been used in this study based on 2/3 PWRs and 1/3 BWRs reflecting the current percentages of reactor types in the economy (as of 1978).

³The term "metallic uranium" is used here, not to indicate the physical form of the uranium, but to indicate that mass values refer only to the element uranium, regardless of chemical compound in which the uranium may be.

Table 4.3

REPRESENTATIVE REPROCESSING EXPANSION SCHEDULES
(1985-2050; MTHM/yr)

Year	Expansion Path 1							Expansion Path 2							Expansion Path 3							Unsuccessful Reprocessing Futures				
	A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G	4	5	6	7	8
1985	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	0	0	0	0	0	0	0	1500	1500	0	0	0
86	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
87																										
88			3000	3000	3000	3000	3000																			
89		↓	↓	↓	↓	↓	↓																			
1990		3000	↓	↓	↓	↓	↓								1500	1500	1500	1500	1500	1500	1500			1500	1500	
91		↓	4500	4500	4500	4500	4500								↓	↓	↓	↓	↓	↓	↓					
92		↓	↓	↓	↓	↓	↓								↓	↓	↓	↓	↓	↓	↓					
93	3000	↓	↓	↓	↓	↓	↓								↓	↓	↓	↓	↓	↓	↓					
94	↓	4500	6000	6000	7500	9000	12000	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500					
1995	↓	↓	↓	↓	7500	9000	12000	↓	↓	↓																
96			↓	↓	9000	12000	15000										0	0								
97		6000	7500	↓	12000	15000	15000			3000																
98		↓	↓	↓	15000	15000	15000			↓																
99		↓	9000	↓	15000	18000	↓			↓																
2000	4500	↓	↓	12000	13500	15000	↓			3000																
1	↓	7500	↓	↓	↓	16500	↓			↓																
2			10500	↓	15000	↓	↓			↓																
3		↓	↓	13500	↓	↓	↓			4500																
4		↓	↓	↓	↓	↓	↓			6000																
2005	4500	7500	10500	13500	15000	16500	18000			↓																
2010	3000	6000	9000	10500	13500	15000	15000	4500	6000	7500																
2015	2000	4500	7500	9000	10500	13500	15000	4500	7500	9000																
2020	1500	3000	6000	7500	7500	10500	10500	3000																		
2025	↓	3000	3000	4500	6000	9000	7500	3000																		
2030		3000	1500	1500	3000	6000	4500	1500																		
2035		1500	1500	1500	3000	3000	3000																			
2040	↓	1500	1500	1500	1500	1500	1500																			
2045	--	--	--	--	--	--	--																			
2050	--	--	--	--	--	--	--																			

Enrichment fuel flow is governed by the relation:

$$F/P = (x_p - x_w)/(x_f - x_w)$$

where P = Product Stream, F = Feed, x_p = product enrichment (.711% for natural uranium), and x_w = tails assay concentration .

In the decision tree of Figure 4.1, eight reprocessing expansion paths were identified, with a ninth representing the open-cycle or no-reprocessing case. The differences between paths 1 - 3 reflect different assumptions regarding reprocessing market introduction rates. Along paths 4 - 8, the industry does not expand because of economic or technical failure, or government censure. The differences in economic benefits between the permit and delay options is sensitive to assumptions made concerning reprocessing expansion rates, and the resulting expansion schedules. Assumptions made in this study include:

- (i) The study period is split into two time intervals; from 1975-2005 reflecting the near term future of reprocessing, and from 2005-2050, reflecting the long term future of reprocessing. The costs of operating the nuclear fuel cycle are considered only between these years; the study is truncated at the year 2050;
- (ii) It is assumed that the reprocessing of spent fuel takes place soon after its removal from the reactor , allowing for up to a one year residence time in reactor spent fuel ponds before being shipped to the reprocessor-MOX fabrication facility. Reprocessors and MOX fabricators are assumed scheduled and built to meet demand such that no prolonged storage of plutonium or spent fuel need take place.

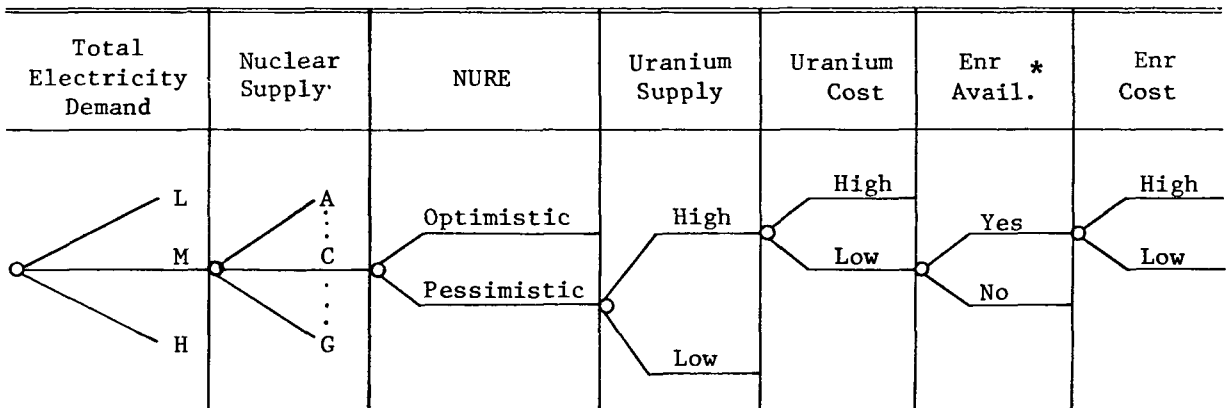
Reprocessing capacity expansion schedules used in this study are described in Table 4.3.⁴

⁴ Resulting fuel flows corresponding to each reprocessing expansion path in the decision tree are given as a function of nuclear supply for the years 1975-2050, in addition to separative work savings in SWU, reprocessing, MOX fabrication, and HLW disposal requirements (Appendix B.1, Tables B.1-3).

From the fuel differences resulting from the recycle of recovered products (see Appendix B.1), deterministic outcome values are calculated as a function of future possible economic states-of-the-world. Economic states that reprocessing expansion paths share in common include total electricity demand, nuclear (LWR) supply, the outcome of the NURE study, and front-end fuel cycle process factors (Figure 4.3). With regard to back-end fuel cycle operations, expansion paths 1 - 8 share reprocessing, MOX fabrication, and high-level waste disposal costs in common, while path 9, the open cycle path, includes only spent fuel temporary and permanent storage costs.

Figure 4.3 Economic States-of-the-World

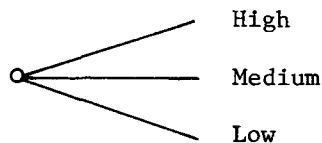
a. Economic States Shared in Common Between Reprocessing and No Reprocessing Expansion Paths



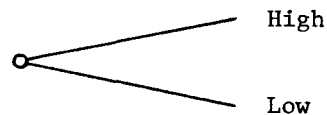
*"Enr" refers to enrichment.

b. Economic States that Differ Between Expansion Paths

Reprocessing/MOX
Fabrication and
HLW Disposal Costs



Cost of Spent Fuel
Permanent Disposal



Outcome values in dollar terms are calculated for each economic state-of-the-world through the definition of cost states associated with the nine defined reprocessing expansion paths (Table 4.4).

Table 4.4

COST STATES
(200 Defined)

a. Reprocessing Paths 1 - 8*

Cost State	Uranium Cost		Enrichment Cost		Rep/Fab/HLW Cost			Spent Fuel Storage Cost	
	H	L	H	L	H	M	L	H	L
1 (13)	1		1		1			1	(1)
2 (14)	1		1			1		1	(1)
3 (15)	1		1				1	1	(1)
4 (16)	1			1	1			1	(1)
5 (17)	1			1		1		1	(1)
6 (18)	1			1			1	1	(1)
7 (19)		1	1		1			1	(1)
8 (20)		1	1			1		1	(1)
9 (21)		1	1				1	1	(1)
10 (22)		1		1	1			1	(1)
11 (23)		1		1		1		1	(1)
12 (24)		1		1			1	1	(1)

*Cost states in parentheses refer to cases where spent fuel storage costs are low rather than high.

b. Open Cycle Path 9

Cost State	Uranium Cost		Enrichment Cost		Spent Fuel Storage and Disposal Cost	
	H	L	H	L	H	L
1	1		1		1	
2	1		1			1
3	1			1	1	
4	1			1		1
5		1	1		1	
6		1	1			1
7		1		1	1	
8		1		1		1

Table 4.5

VALUE ASSUMPTIONS AND PRIOR ASSIGNMENTS ON KEY UNCERTAINTIES (1975 \$)*

1985	1995	Determined at Date of First Commercialization																																																								
<p>NURE-- Estimates on 10⁶ ST U₃O₈ @ 35 \$/lb</p> <p>(optimistic) .6 — 3.78 (pessimistic) .4 — 1.76</p>	<p>Uranium Supply</p> <p>Opt. NURE Pess. NURE</p>	<p>Rep Fab HLW</p> <p>Cost of Reprocessing/MOX Fabrication/HLW Disposal (\$/kgHM)</p> <p>.25 — 350 300 90 .50 — 250 200 70 .25 — 150 150 50</p>																																																								
<p>Total Electricity Demand TkwH yr 2000</p> <p>.6 — 4 .3 — 5 .1 — 6</p>	<p>Priors conditional on NURE:</p> <p>Opt. P_H .7 Pess. P_L .3</p>	<p>Cost of Spent Fuel Permanent Disposal (\$/kgU)</p> <p>.5 — 200 .5 — 100</p>																																																								
<p>Nuclear Supply; GWe yr 2000</p> <p>A — 120 C — 360 E — 600</p>	<p>Uranium Cost (\$/lb U₃O₈)</p> <p>P_H — 75 P_L — 35</p>	<p>1995 Enrichment Capacity Availability</p> <p>P_Y — Yes P_N — No</p>																																																								
<p>Priors Conditional on Total Electricity Demand:</p> <table border="1"> <thead> <tr> <th>TKWH</th> <th>P_A</th> <th>P_B</th> <th>P_C</th> <th>P_D</th> <th>P_E</th> <th>P_F</th> <th>P_G</th> </tr> </thead> <tbody> <tr> <td>4</td> <td>.05</td> <td>.15</td> <td>.34</td> <td>.22</td> <td>.14</td> <td>.07</td> <td>.03</td> </tr> <tr> <td>5</td> <td>.03</td> <td>.09</td> <td>.20</td> <td>.30</td> <td>.20</td> <td>.12</td> <td>.06</td> </tr> <tr> <td>6</td> <td>.02</td> <td>.07</td> <td>.12</td> <td>.18</td> <td>.30</td> <td>.20</td> <td>.11</td> </tr> </tbody> </table>	TKWH	P _A	P _B	P _C	P _D	P _E	P _F	P _G	4	.05	.15	.34	.22	.14	.07	.03	5	.03	.09	.20	.30	.20	.12	.06	6	.02	.07	.12	.18	.30	.20	.11	<p>Priors conditional on LWR supply and Uranium Availability:</p> <table border="1"> <thead> <tr> <th></th> <th>A H L</th> <th>B H L</th> <th>C H L</th> <th>D H L</th> <th>E H L</th> <th>F H L</th> <th>G H L</th> </tr> </thead> <tbody> <tr> <td>P_H</td> <td>.1.2</td> <td>.1.2</td> <td>.1.3</td> <td>.2.3</td> <td>.2.4</td> <td>.3.5</td> <td>.3.5</td> </tr> <tr> <td>P_L</td> <td>.9.8</td> <td>.9.8</td> <td>.9.7</td> <td>.8.7</td> <td>.8.6</td> <td>.7.5</td> <td>.7.5</td> </tr> </tbody> </table>		A H L	B H L	C H L	D H L	E H L	F H L	G H L	P _H	.1.2	.1.2	.1.3	.2.3	.2.4	.3.5	.3.5	P _L	.9.8	.9.8	.9.7	.8.7	.8.6	.7.5	.7.5	<p>Cost of Enrichment (\$/kgSWU)</p> <p>P_H — 125 P_L — 75</p> <p>P_H P_L Y .5 .5 N .7 .3</p> <p>Priors conditional on enrichment capacity availability</p>
TKWH	P _A	P _B	P _C	P _D	P _E	P _F	P _G																																																			
4	.05	.15	.34	.22	.14	.07	.03																																																			
5	.03	.09	.20	.30	.20	.12	.06																																																			
6	.02	.07	.12	.18	.30	.20	.11																																																			
	A H L	B H L	C H L	D H L	E H L	F H L	G H L																																																			
P _H	.1.2	.1.2	.1.3	.2.3	.2.4	.3.5	.3.5																																																			
P _L	.9.8	.9.8	.9.7	.8.7	.8.6	.7.5	.7.5																																																			

* Detailed discussion of prior derivations is found in Appendix B.3.

C. Probabilistic Phase: Scenario Event Likelihoods

Value assumptions and prior distributions on key parameters are defined in Table 4.5, with detailed derivations provided in Appendix B.2. The expected value for each reprocessing expansion path fuel cycle system cost is then calculated, leading to expected value direct economic benefits for each decision option (Figure 4.4).

Figure 4.4 Expected Value of Reprocessing Direct Economic Benefits*
(Billions of 1975 Dollars)

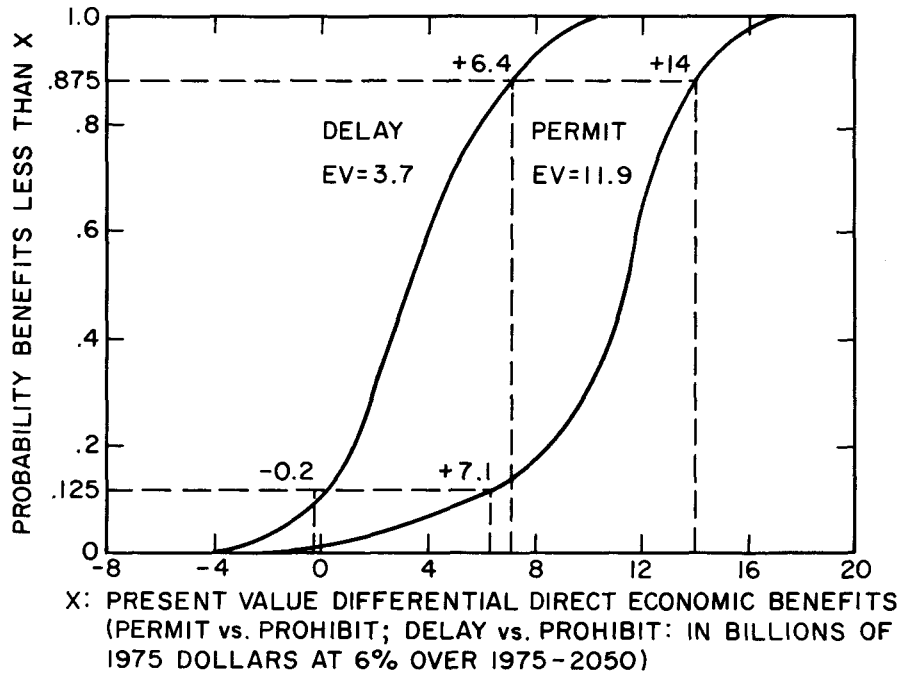
		Social Discount Rate			
		0%		6%	
		1975-2005	2006-2050	1975-2005	2006-2050
□	Permit	28.3 (.54)	36.6 (.70)	8.7 (.75)	3.2 (.28)
	Delay	9.9 (.19)	12.8 (.25)	2.6 (.22)	1.1 (.10)
	Prohibit	0 (0)	0 (0)	0 (0)	0 (0)

*Discounted to 1975; equivalent mills/kWh savings shown in parentheses.

These results are the expected values of probability distributions that represent the outcomes as probabilistic value lotteries (Fig. 4.5). Reasons for exhibiting the results in this way include: (1) to indicate how wide a dispersion of possible values exists for each option, and (2) to demonstrate whether or not a particular option strongly dominates the others. From the results shown here, the permit option stochastically dominates delay while exhibiting the wider dispersion of values. That is, for the author's assigned base-case priors, an expected value of 11.9 billion dollars discounted @ 6% over 1975-2050 is calculated for the permit option, where the likelihood that the benefits will fall between 7.1 and 14 billion dollars is found to be .75, and the likelihood the benefits would be positive is greater than 95%. For delay, the expected value direct benefits are calculated to be 3.7 billion dollars at 6% over the years 1975-2050, where a likelihood of .75 exists that the

benefits would fall between $-.2$ and 6.4 billion, where the likelihood the benefits assume a negative value (implying prohibit the preferred alternative over delay) is 13%.

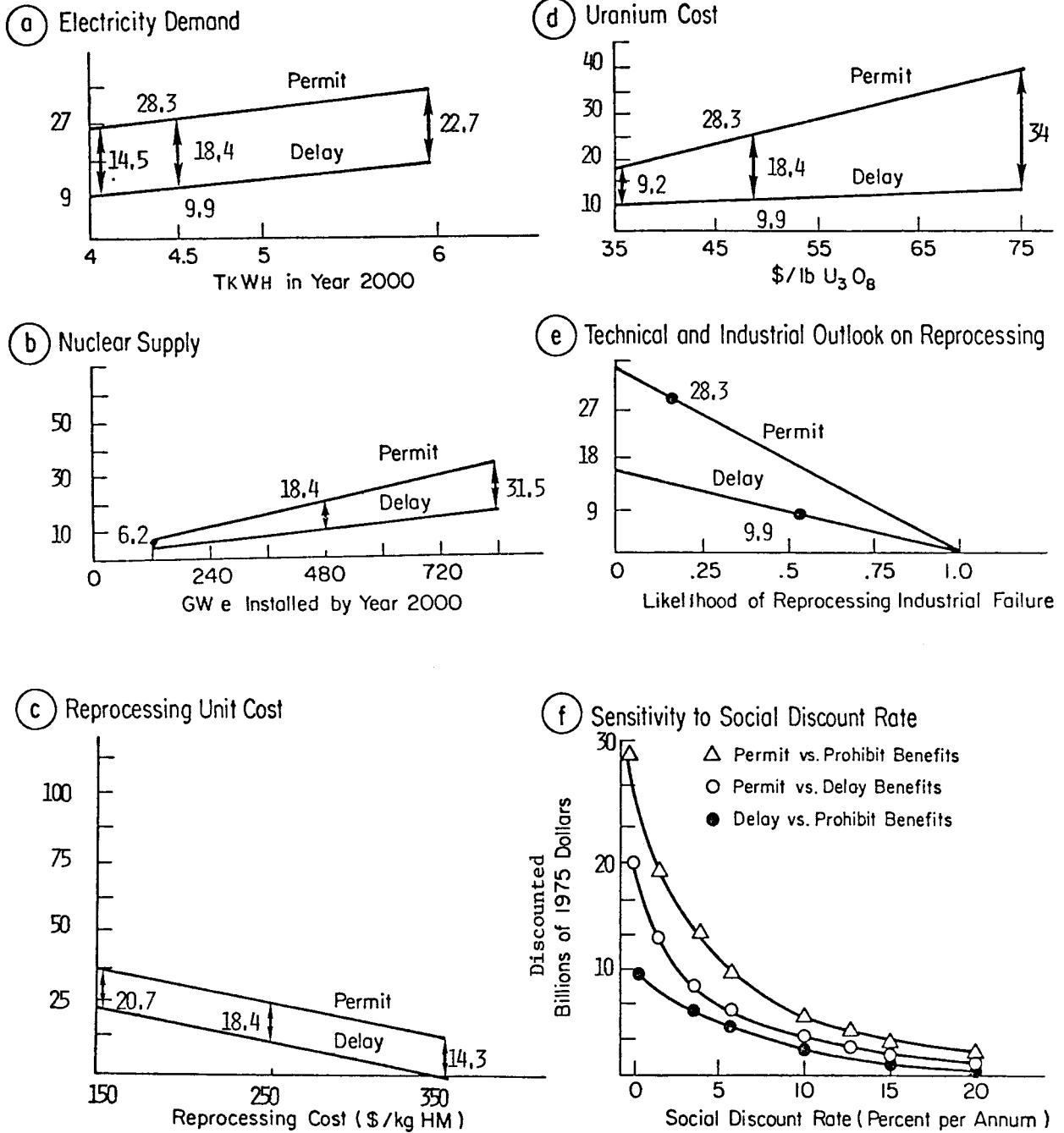
Figure 4.5 Direct Economic Benefits Expressed as Cumulative Probabilistic Value Lotteries



D. Sensitivity Analysis

To demonstrate how the expected value direct economic benefits vary as a function of changes in the state-of-information regarding key parameters, a stochastic sensitivity analysis has been conducted. That is, the sensitivity of the results to the author's base-case probability assignments on key parameters is tested. The analysis is conducted by sequentially assigning a certain value to each variable while adjusting all other priors on variables as necessary, reflecting any conditionality relationships existing between variables. Then results are recalculated, and any changes in the expected values are plotted. The sensitivity of the decision to such changes is plotted in Fig. 4.6, a-f. The analysis indicates that permit remains dominant over both delay and prohibit options, except for the case where reprocessing costs assume certain values over

Figure 4.6 Sensitivity Analysis: Direct Economic Benefits
(Billions of 1975 Undiscounted Dollars in (a)-(e))



450 \$/kg HM; in that case, prohibit becomes optimal over both prohibit and delay. Note that permit dominates prohibit dominates delay when re-processing cost assumes a certain value of 350 \$/kg HM, but that in no case does delay become dominant over permit.⁵

⁵The economic models have been truncated at the year 2050. End effects that arise are therefore minimized when a positive discount rate is used. That is, the assumption is made that benefits-costs arising beyond the year 2050 are negligible since the relatively long model time span tends to compensate for end effects. This is equivalent to assigning a zero salvage value on fuel cycle facilities still operable after the year 2050.

Chapter 5

INDIRECT ECONOMIC BENEFITS DUE TO REPROCESSING DECISION INFLUENCE ON BREEDER COMMERCIALIZATION DATE

Unless alternative sources of electrical energy become practical -- even in nations having extensive commercial grade coal deposits -- nuclear may become the preferred energy cycle of choice. If systems to extend the life of scarce fissile resources are constrained through prohibition of spent fuel reprocessing or failure of breeder technologies, nuclear options for future generations may be foreclosed. Thus, *costs of constraining nuclear power* may also be inter-generational.

-- William R. Harris [65]

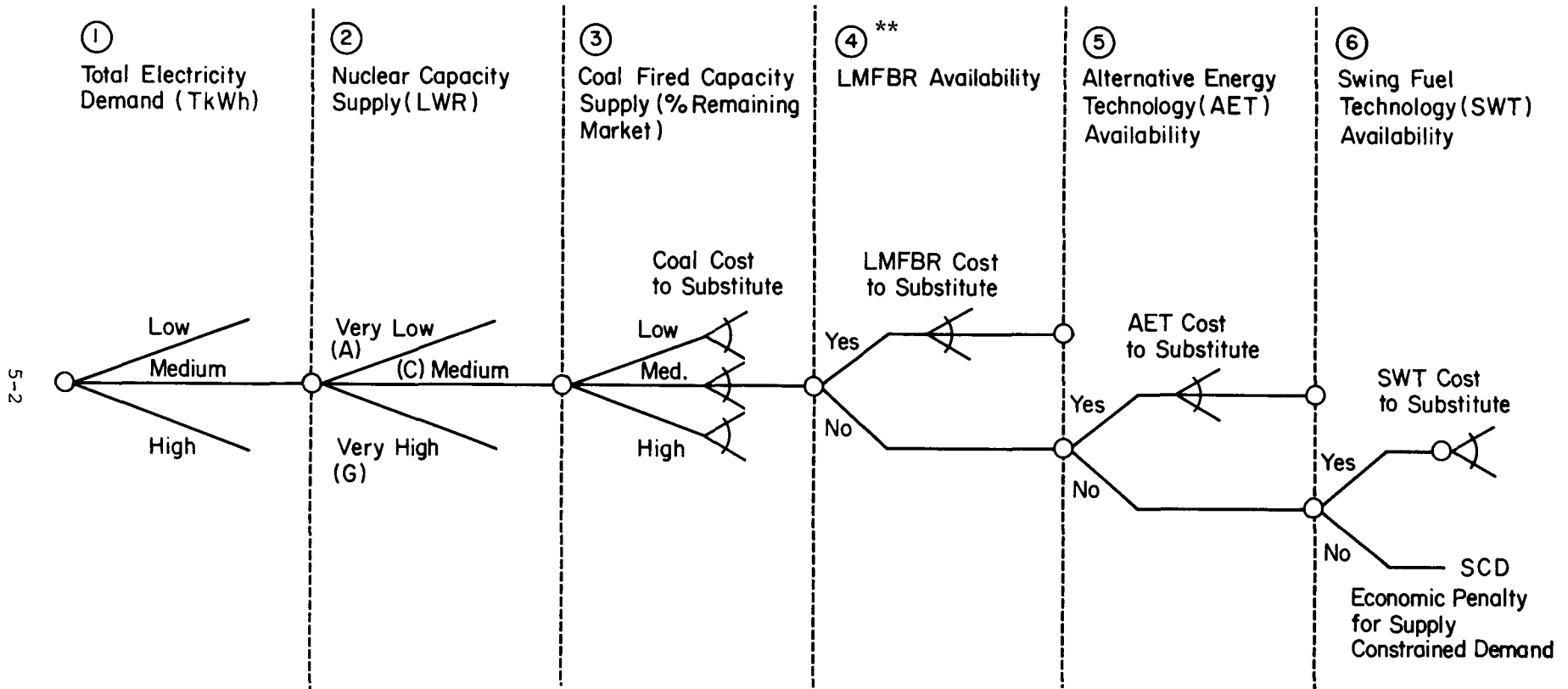
Overview

This chapter examines the impact of the reprocessing decision on breeder benefits and nuclear power expansion rates. These are defined as the "indirect" economic benefits resulting from the reprocessing decision. The relationship between reprocessing, the breeder, and LWR commercial expansion rates has not been addressed in most previous reprocessing economic studies.¹ However, unless alternative energy technologies become practical near the end of this century, nuclear fission may be called upon to play a larger role in satisfying energy demand in the coming century. Thus, significant long-term benefits may arise from pursuing the development of reprocessing and the breeder in a timely fashion during this century. That is, the potential economic costs of constraining nuclear power cannot be ignored when deciding between reprocessing alternatives.²

¹One study which has included this relationship is that of Manne and Richels [17].

²The indirect benefits resulting from a timely pursuance of today's nuclear power technologies (or costs of not doing so) are not only of the economic variety. For nations which might incur higher energy costs as a result of nuclear constraints (e.g., the U. S.), oil-import dependence may induce balance-of-payment and foreign policy costs (p. 14, [66]).

Figure 5.1 U.S. Electricity Supply States-of-the-World*



* Supply States-of-the-World are modeled for four time periods:

(1) 1975-1995, (2) 1996-2015, (3) 2016-2035, and (4) 2036-2050.

** If reprocessing is prohibited, then a zero likelihood is assigned to the event of LMFBR availability within any given time period.

A. The Fuel Substitution Model

The indirect economic benefits of reprocessing are estimated through the use of an event tree description of possible U.S. electricity supply states-of-the-world (Figure 5.1). To determine the undersupply costs due to a shortage of nuclear capacity, a range on the percentage electricity demand that LWR capacity is built to supply is established as a function of time (see Appendix C). Then a range on the percentage electricity demand that coal-fired capacity supplies is determined, with the remainder of demand assumed to be satisfied by swing fuels such as oil and natural gas, or alternative energy technologies (AET). The number of available alternative technologies is expected to increase as time progresses, based on the assumption that new technological developments will take place in the future that will make these alternatives commercially attractive. The additional assumption is made that, as time progresses, oil and gas alternatives will be phased out because of depleting fuel supplies, higher prices, and legislation against prolonged usage.

Finally, for the case where demand exceeds supply, an economic penalty is assigned, reflecting society's *willingness to pay* for the additional capacity required to meet unconstrained demand. A value of 100 mills/kWh is used to represent this penalty; i.e., loss of welfare because of lack of supply to meet electrical demand (see Appendix C.1).

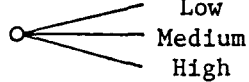
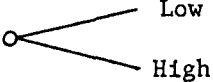
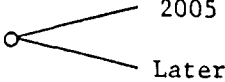

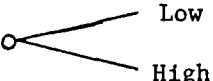
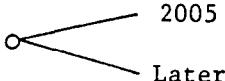
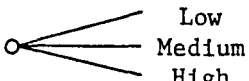
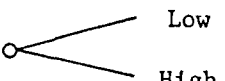
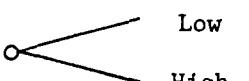
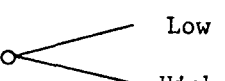
B. Prior Assignments

Key uncertainties that influence indirect benefits include fuel costs of substitution measured relative to LWR mills/kWh electricity generating costs, and the commercial availability of the technologies in the indicated time period (i.e., date of commercial introduction). Key uncertainties are listed relative to assumed dates of resolution (Table 5.1), with value assumptions and prior assignments used in the model base case described (see Appendix C.2).

Crucial to the calculation of overall substitution costs are assumptions on coal fired capacity supply and mills/kWh cost to substitute for LWRs. However, the more significant uncertainty that affects indirect cost-benefits between reprocessing decision options is the LMFBR date of introduction and subsequent rate of growth. Since the LMFBR is a reprocessing dependent technology, and must initially be fueled by plutonium,

Table 5.1

DATES-OF-RESOLUTION OF KEY UNCERTAINTIES

1985		1995		2005	
Total Electricity Demand		Coal Cost to Substitute		LMFBR Date-of-Introduction	
Nuclear Capacity Supply *		Swing Fuel Cost to Substitute		AET Date-of-Introduction	
Coal Capacity Supply				LMFBR Cost to Substitute	
Swing Fuel Capacity Supply				AET Cost to Substitute	

* Spans a wide range of supply scenarios; hence the dotted notation.

to prohibit reprocessing in LWRs must logically imply the prohibition of the development of a plutonium based LMFBR. To delay the commercial introduction of reprocessing in LWRs would appear to imply the increased likelihood of a delay in the commercialization of the reprocessing dependent LMFBR. To permit (in 1978) the reprocessing of LWR spent fuel would allow the nuclear industry to immediately initiate the commercialization and expansion of the reprocessing industry, thus providing the technical and industrial infrastructure required for the development of a commercial scale LMFBR industry. Thus, the implication is that only with a positive decision on reprocessing (the permit option) could the LMFBR become a realistic near-term (i.e., pre-2000) alternative to American utilities. That is, priors on the date of commercial introduction of the LMFBR into the U.S. economy are shifted further out in time the longer the reprocessing decision is delayed (see Appendix C.2.5).

C. Expected Value Benefits

For base case assumptions and priors made on key uncertainties, the expected value benefits associated with reprocessing decision alternatives have been calculated (Figure 5.2).

Figure 5.2 Expected Value Indirect Economic Benefits* (Billions of 1975 Dollars)

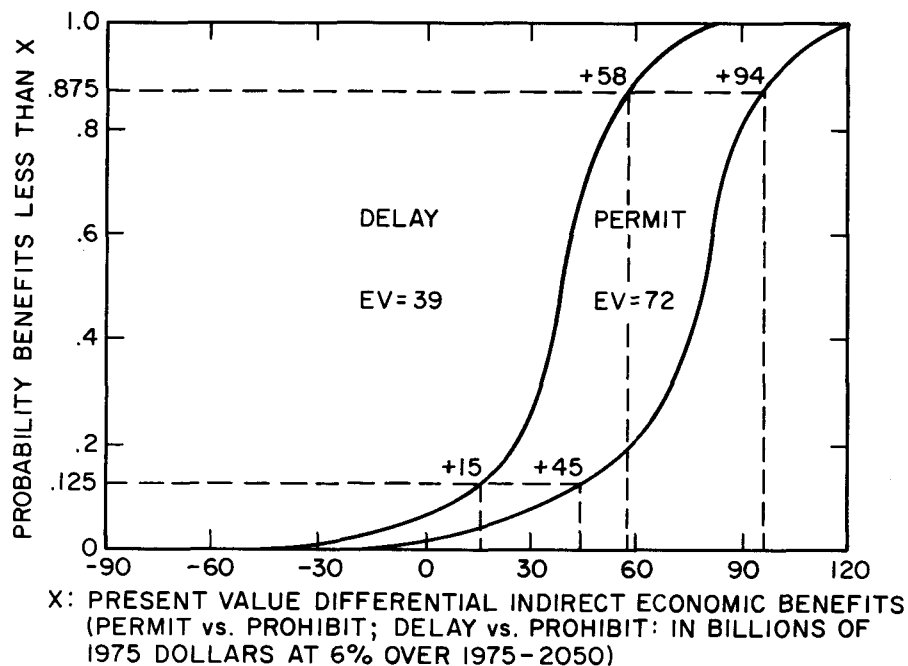
		Social Discount Rate			
		0%		6%	
		1975-2005	2006-2050	1975-2005	2006-2050
□	Permit	15.3 (1.33)	1585 (29.1)	0.7 (.06)	71.2 (6.18)
	Delay	1.6 (.14)	914 (17.3)	0.1 (.01)	38.5 (3.35)
	Prohibit	0 (0)	0 (0)	0 (0)	0 (0)

*Discounted to 1975; equivalent mills/kWh savings shown in parentheses.

These results represent the expected values of probabilistic value lotteries on the indirect differential benefits calculated between permit and prohibit, and delay and prohibit options (Figure 5.3). The permit option appears to stochastically dominate that of delay. That is, for any value X, there exists a higher probability of the benefits exceeding this value with the permit alternative than with the delay alternative (i.e., the permit curve lies below that for the delay curve for every value X). The diagram also indicates that both delay and prohibit options dominate the prohibit option, as a likelihood of ~5-10% is associated with the event that the benefits assume negative values for delay or permit, implying positive benefits with prohibition.

For the author's assigned base case priors, an expected value of 71.9 billion dollars discounted @ 6% over 1975-2050 is calculated for the permit option, where a likelihood of .75 exists that the benefits fall between 45 to 94 billion dollars and the likelihood of positive benefits exceeds .95. For delay, an expected value of 38.6 billion dollars was calculated, where a likelihood of .75 exists that the benefits fall within 15 to 58 billion dollars. A likelihood of ~10% exists that prohibit would dominate delay (i.e., delay would imply negative benefits).

Figure 5.3 Indirect Economic Benefits Expressed as Cumulative Probabilistic Value Lotteries

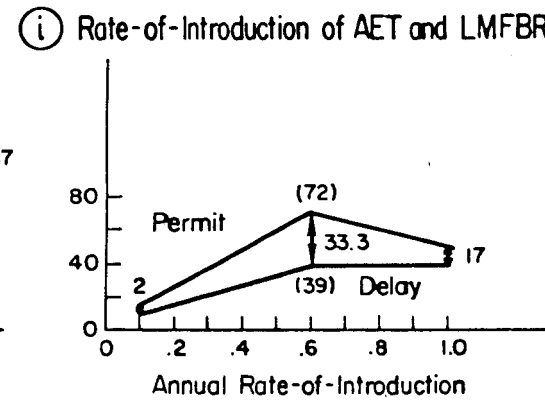
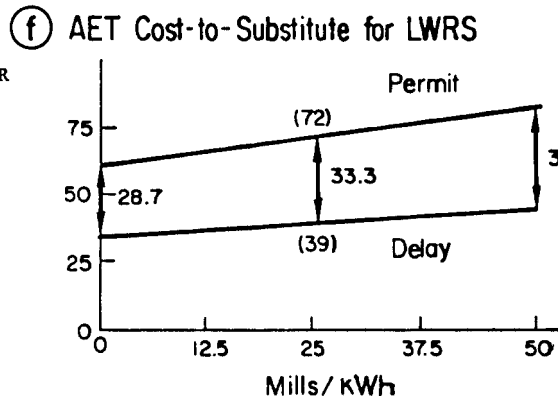
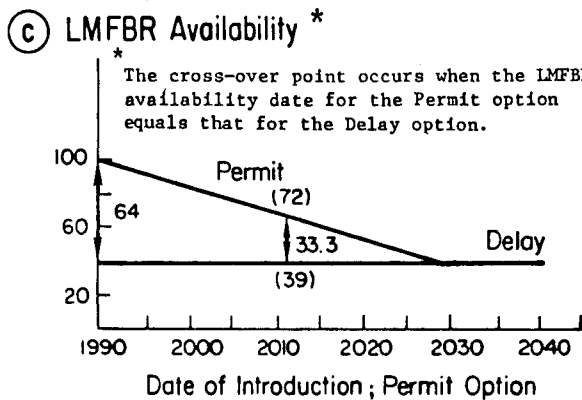
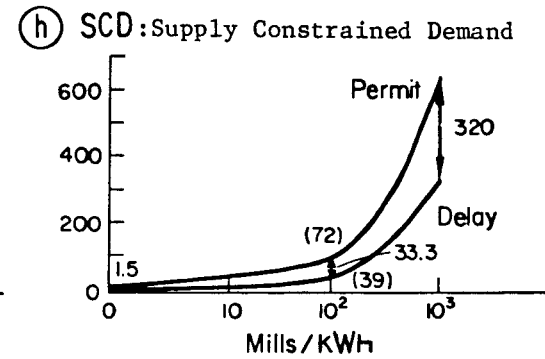
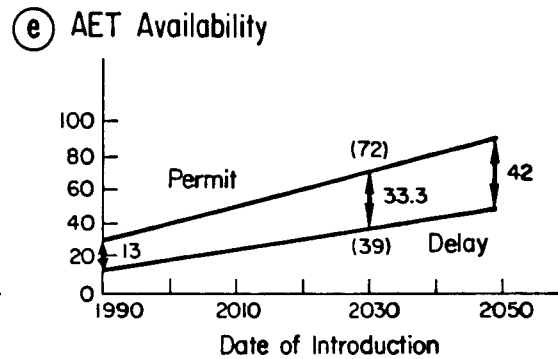
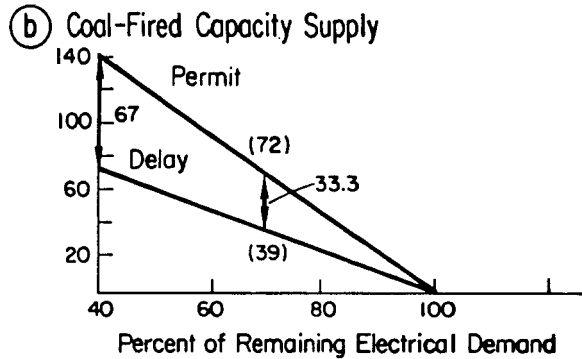
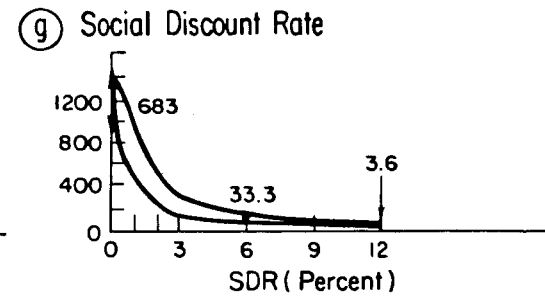
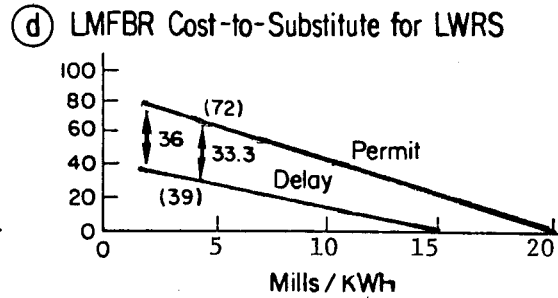
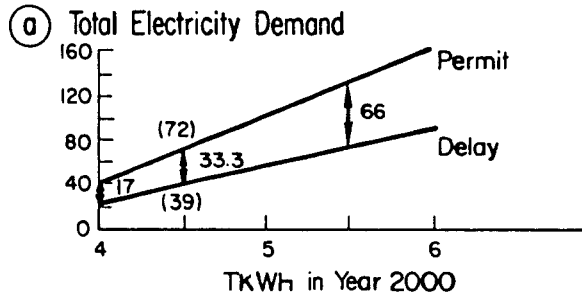


D. Sensitivity Analysis

The sensitivity of the expected value results to changes in the state-of-information regarding key parameters was next analyzed by conducting a stochastic sensitivity analysis (Fig. 5.4). For all cases examined, the expected value benefits associated with the permit alternative are greater than those for delay or prohibit options, except when the differential electrical generating costs between the LWR and LMFBR exceed ~ 20 mills/kWh (1975 dollars). In that case, prohibit dominates both delay and permit alternatives. Also, the benefits between options vanishes for the case where coal fired capacity meets all electrical demand not satisfied by LWR capacity. In that case, the breeder and other alternative energy technologies would not be required; hence, zero benefits are associated with LMFBR development.

Breeder benefits also decrease for those scenarios in which the AET is introduced before the year 2000; the more readily available an alternative energy source, the less valuable the introduction of a breeder reactor system. However, if these alternatives are not available until much later, breeder benefits increase (see Fig. 5.4e). As is shown in Fig. 5.4c, indirect benefits between permit and delay options vanish if it is assumed that the reprocessing decision does not influence the commercialization date of the LMFBR. However, for delays in breeder commercialization of more than 20 years due to a delay in reprocessing and development of the plutonium economy in LWRs, the greater the implied differences in breeder benefits between permit and delay options. The results also indicate that breeder benefits are larger in those cases where total electricity demand is greater than 4.5 TkWh in the year 2000, cases that might easily occur given a return to historical electrical growth rates.

Figure 5.4 Sensitivity Analysis: Indirect Benefits (Billions of 1975 Dollars Discounted to 1975 @ 6%)



Chapter 6

DOMESTIC TECHNOLOGICAL RISKS LEADING TO SOCIAL COSTS

We are concerned, as in so much of human life, with decisions between what may seem incommensurables, but which have to be measured. These are matters involving both comfort and culture, bread and suffering, a standard of living and a quality of life -- literally both life and death. We have, inescapably, to treat them *by measure*; how much life? how much death?

-- Denys Munby [67]

What is our society willing to pay for safety?

-- Chauncey Starr [68]

Overview

Risk is associated with almost any technological endeavor.¹ In choosing between alternatives, it is the relative risk between options that must be assessed. In this chapter, reprocessing risks are compared with those of not reprocessing by examining the hazards associated with open and closed fuel cycles (Figure 6.1). Risks examined include: (i) health, environmental and safety, and (ii) nuclear theft and sabotage.

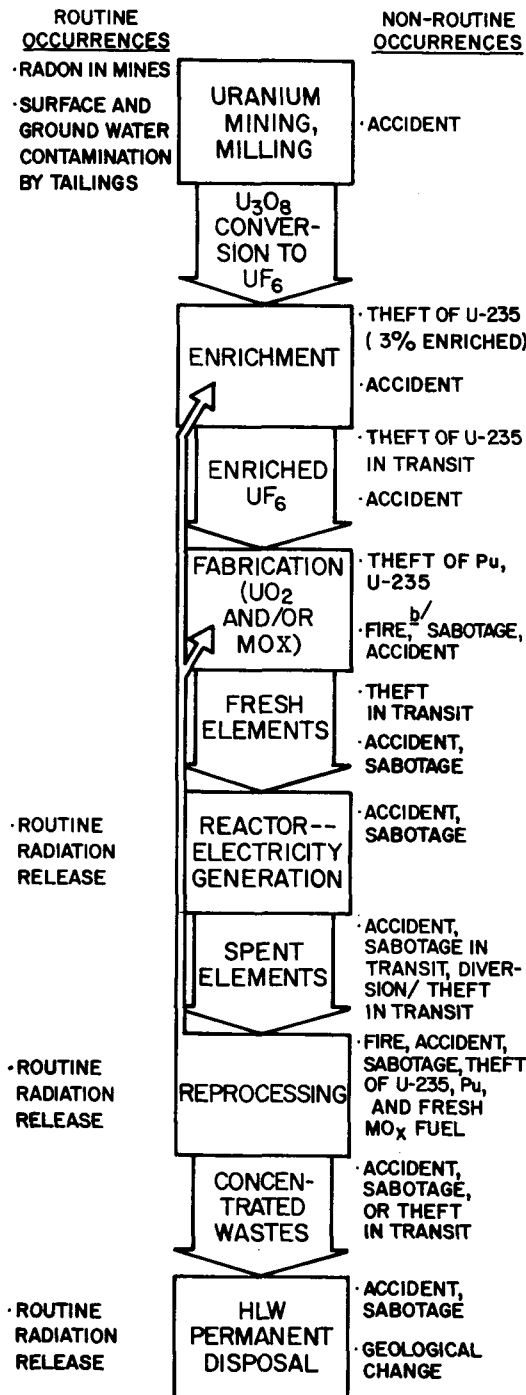
In quantifying social costs due to fuel cycle risks, emphasis is placed on how much society is willing to pay to reduce risk,² since the trade off between risk reduction and health, safety and safeguards expenditures follows the economic law of diminishing returns. That is, the marginal return per dollar spent decreases as the absolute cost of added

¹A risk is defined as an uncertain, unpredictable event measured in terms of potential outcome and probability of occurrence. Risks can be described as lotteries, either continuous or discrete, that relate outcomes to their probability of occurrence [69-74].

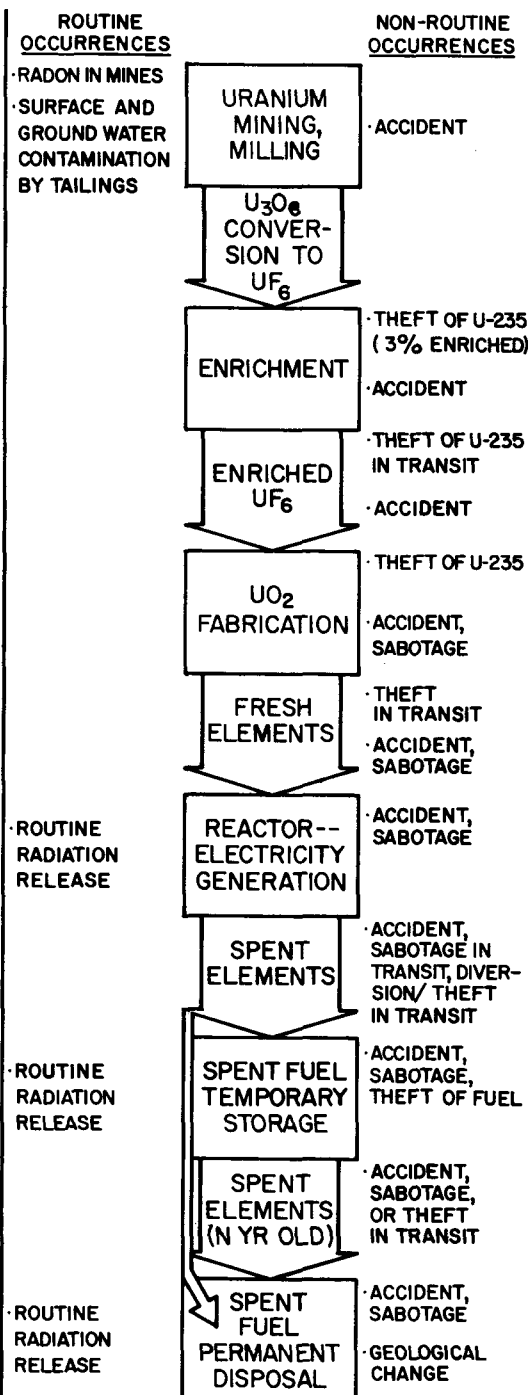
²Linnerooth has summarized methods for assessing the value of life-saving: (i) the human capital approach, (ii) the implicit societal evaluation approach, (iii) the insurance premium and court-decided compensations approach, and (iv) the risk approach. The risk approach makes use of the certain equivalent concept, defined as the amount society is *willing to pay* to reduce risk, and is used in this work [75,76].

Figure 6.1 Relative Hazards of the Closed Versus Open Fuel Cycles ^{a/}

I. REPROCESSING (U & Pu RECYCLE)--CLOSED CYCLE



2. NO REPROCESSING--OPEN CYCLE

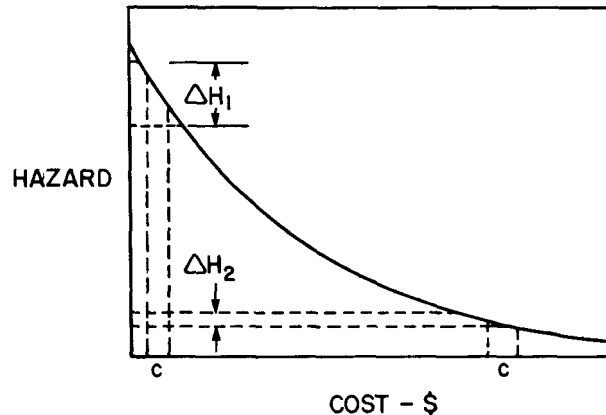


^{a/} EXCLUSIVE OF PROLIFERATION RELATED HAZARDS

^{b/} REFERS TO PLUTONIUM FIRE

improvements increase (Figure 6.2). The question becomes one of determining the level at which the marginal return per unit cost can no longer justify the continued expenditures -- a social value judgment.

Figure 6.2 Cost Effectiveness of Increased Expenditures to Reduce Risk

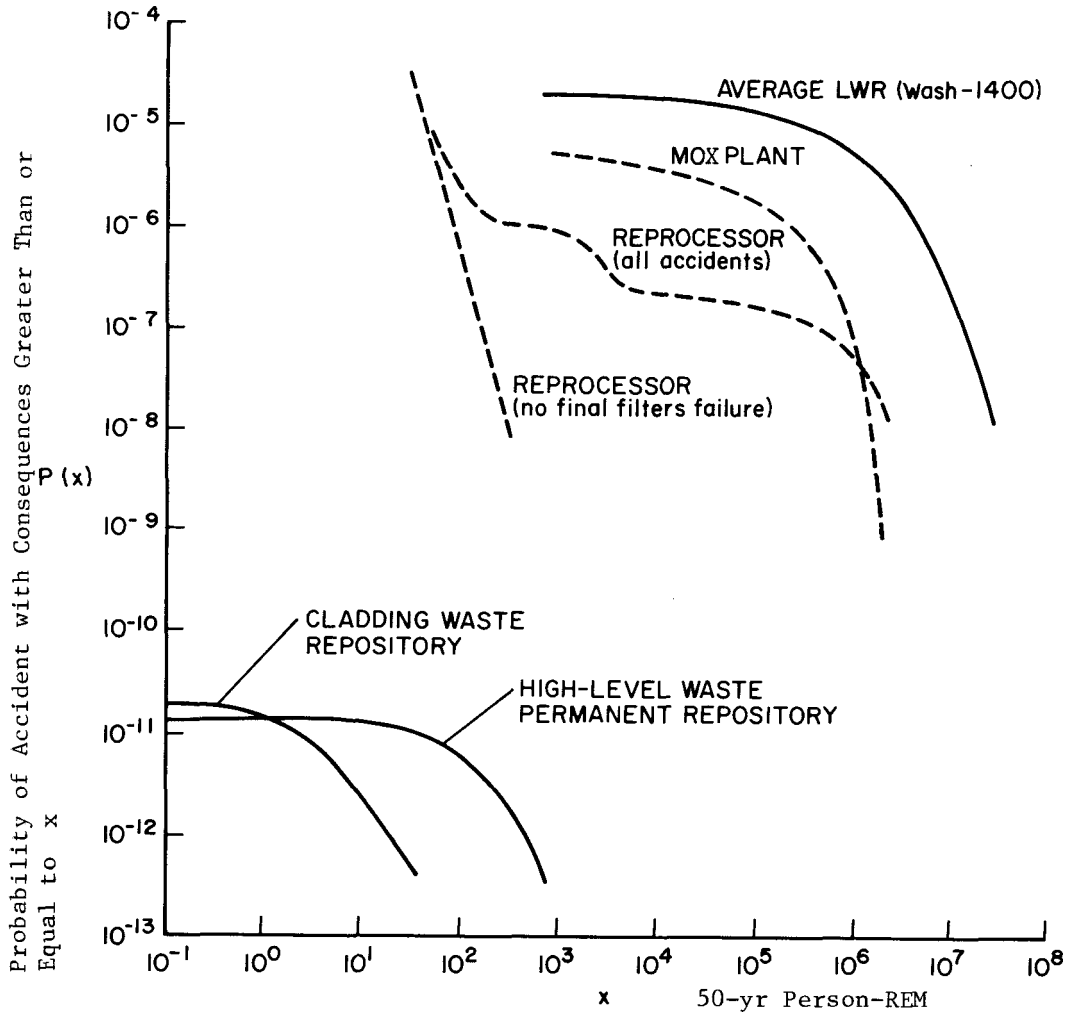


A. Health, Environmental and Safety Risks

The nuclear fuel cycle, regardless of *modus operandi*, poses risks to the environment and the the health and safety of persons employed at or living near fuel cycle facilities. An environmental risk is defined as one that places some component of the environment in danger of contamination or damage as a result of routine facility operation. A health risk is defined as one that jeopardizes the health of those members of society who are routinely exposed to facility operations for occupational or residential reasons. Finally, a safety risk is defined as one that places both the environment and health of society members in danger as a result of an unintentional non-routine occurrence, such as an accident or fire (Table 6.1).

Several studies have assessed nuclear fuel cycle health, environmental and safety risks. Sagan studied health and safety risks, inclusive of non-radiation related occupational injury (August 1972, [78]). Teknekron compared the risks of accidents with risks of normal operations in the fuel cycle (November 1975, [79]). The Nuclear Regulatory Commission (NRC)

Figure 6.3 Comparison of Accident Probabilities and Consequence Levels for Various Nuclear Facilities (Consequence x in 50-Yr Person-REM)



Note: The MOX fabrication plant services the annual requirements of 16 1-GWe LWRs; the reprocessor, 50 LWRs per year. The HLW repository houses the waste generated by 280 LWRs per year. For spent fuel permanent disposal, the results for the HLW repository represent a close approximation (p.6, [82]; [83]).

Table 6.1
 CLASSIFICATION OF HEALTH, ENVIRONMENTAL AND SAFETY RISKS
 BY OCCURRENCE TYPE AND MAJOR SOCIAL GROUP AFFECTED

Major Social Group Affected	Routine Occurrence (Health-Environmental Risks)	Non-Routine Occurrence (Safety Risks)
Occupational Personnel	Occupational Radiation Exposure	Injury or Death Due to Major or Minor Accidents and Fires
Local Off-Site Population	Exposure to Routine Radiation Releases	Exposure to Non-Routine Radiation Releases from Accidents and Fires
Distant Off-Site Populations	Negligible Effect	Negligible Effect

assessed radiation induced health and safety risks in the final GESMO study (August 1976, [14]). A study by B. Cohen evaluated the hazards of routine emissions from nuclear installations, the ingestion hazard of high level waste as a function of the time after reprocessing, and power plant and transportation accidents (October 1976, [80]). The American Physical Society (APS) study on the nuclear fuel cycle assessed radiation induced health and safety risks (July 1977, [81]). Also, Science Applications, Inc. (SAI) examined the safety risks of fuel cycle facilities; in particular, reprocessing plants, MOX fabricators, and high-level waste and spent fuel permanent geologic repositories (1977, [82-84]). Other high-level waste disposal risk assessment studies include that of the Analytic Science Corporation [85], and the ongoing (as of 1978) NRC sponsored studies at the Lawrence Livermore and Sandia Albuquerque laboratories (Heckman, et al., [86]; Campbell, et al., [87]). The Department of Energy (DOE) is also sponsoring an ongoing risk assessment of high-level waste disposal at Batelle Northwestern Laboratory (BNWL) (Burkholder, et al., [88]).

A comparison of GESMO and APS study results provides an estimate of between .2-.8 person-REM per MWe -year for the health effect from routine occupational radiation exposure in the fuel cycle (minus the reactor contribution--(Table 6.2)). Using a value of 30-100 \$/person-REM (Sagan, [78]),

Table 6.2

COLLECTIVE OCCUPATIONAL DOSE FROM FUEL CYCLE OPERATIONS
(Person-REM per MWe -Year; Whole Body) [14,81]

Fuel Cycle Stage	GESMO	APS
Mines	0.23	0.1
Mills	0.12	0.1
Fuel Fab & Enrichment	0.01	negligible
Reactors	0.56	1.1
Reprocessing Plants	0.025	0.008-0.6
Other:		
Waste Management	0.002	negligible
Transportation	0.0004	negligible
TOTAL	.95	1.3--1.9
(Minus Reactor)	.39	.2-.8

the social cost per GWe-year is estimated to be on the order of 6 to 80 thousand dollars (1975 terms). When the total off-site population dose is also considered, the social cost due to health effects roughly doubles [14]. All studies indicate that the health related effects due to routine fuel cycle operation dominate the strictly environmental effects. Moreover, the studies conclude that the health and environmental effects between open and closed fuel cycle options are practically indistinguishable (Table 6.3): "With fuel reprocessing and recycle, there are potential *improvements* in overall health and safety in the fuel cycle associated with the decrease in mining and milling. These decreases outweigh, on balance, the additional occupational and environmental exposure attendant to fuel reprocessing and refabrication." (p. 3, Ch. V, [81])

Results of the safety studies indicate that reactor accident risk dominates accident risk in fuel cycle facilities (Figure 6.3).³ Further, accident risks in the reprocessor dominate those in the MOX fabricator,

³For example, see the German study entitled "Studies for Comparing the Greatest Possible Breakdown Consequences in a Reprocessing Facility and in a Nuclear Power Plant" of August 1976 by Bachner, *et. al.* [89].

Table 6.3

ESTIMATED HEALTH EFFECTS OF FUEL CYCLE OPERATION

NRC-GESMO Results (1975-2000) (millions of person-REM)	Reprocessing (U/Pu recycle)	No Reprocessing
U.S. Occupational	3.8	4.1
Offsite	4.2	3.9
U.S. Total	8.0	8.0

high-level waste and spent fuel permanent repositories [83]. Moreover, results indicate that transportation accidents dominate the total fuel cycle accident risk. Should plutonium not be recycled, the total accident risk would be relatively unchanged at the high end of the consequence range, and increased by roughly 30% at the low end of the range. This is the case because of the increase in the required amount of UF₆ conversion, enrichment, and transportation required in the absence of plutonium recycle, which compensates for the reduction in risk from the absence of mixed oxide fuel fabrication and shipments of spent fuel (p. 5-25, [79]). Thus, these results indicate that by closing the fuel cycle, safety risks remain roughly unchanged, or are actually decreased. Teknekron also notes that safety risks are dominated by health and environmental risks from routine fuel cycle operation. Therefore, the social costs due to safety risks are taken as three orders of magnitude less than the social costs due to health risks (i.e., 6-160 dollars per GWe-year in 1975 dollar terms).

Assessment of the more long-term environmental, health and safety risks of high-level waste disposal in geologic repositories indicate that the operational accident risks associated with the short-term pre-sealing history of the repository dominate the long-term risks by many orders of magnitude [85]. However, even these risks are very small; six orders of magnitude less than reactor accident risk for a geologic repository capable of storing the waste from one year's output of 280 1-GWe reactors [82].

In comparing open versus closed fuel cycle risks with regard to the

long-term disposal of spent fuel versus high-level waste, studies note that the gas pathways are more important in the spent fuel case since spent fuel will still contain volatile fission products. However, the short-term handling risks dominate these long-term risks. It was found that accidents during transportation between the reprocessor and final repository, and a massive loss of cooling during interim storage at the reprocessor as a result of a severe earthquake, were the largest contributing events to the expected dose in the closed cycle [82]. These risks dominate the more long-term risks. The disposal of high-level waste would constitute a slightly *lower* risk over the disposal of spent fuel because of the smaller volume of waste that would have to be handled, and the smaller container size [82]. Such considerations would tend to decrease the probability of handling accidents.

Thus, it is concluded that health risks from routine fuel cycle operation dominate the environmental and safety risks, and that differences in health risks between open and closed cycles are indistinguishable. For these reasons, health, environmental and safety social costs are taken to be equivalent between reprocessing and no reprocessing options (6 to 160 thousand dollars per GWe-year, or .001-.03 mills/kWh for CF = 60% in 1975 \$ terms).⁴

B. Nuclear Theft and Sabotage Risks

There exists a wide spectrum of human initiated malevolent actions that might be directed against the domestic nuclear fuel cycle [4]. These acts range from relatively harmless threats and hoaxes, to acts of harassment and disruption of activity, to acts of sabotage and nuclear theft. In this section, the more serious risks of sabotage and nuclear theft are examined, and expected value consequences calculated.

Nuclear theft represents a three-fold risk to society in that stolen materials might be used for purposes of: (i) Extortion -- to derive payments

⁴Excludes the contribution from the reactor. Note that any attempt to distinguish between open and closed fuel cycles on the basis of environmental or safety risks is lost in the uncertainty surrounding the appropriate value associated with the health effects of low-level radiation, expressed in \$ per person REM .

and demands from society as a consequence of a nuclear blackmail attempt, (ii) Dispersal -- to contaminate the environment and cause illness or death in affected populations, and (iii) Fabrication -- to build crude nuclear explosives for use by terrorists or other criminal groups.⁵ Sabotage risks fall into two categories: (i) Damage -- acts leading to physical damage of the facility resulting in financial loss, and (ii) Accident Initiation -- acts leading to accident initiation, with consequences marginally upper bounded by the effects of the maximum credible accident postulated for the particular facility affected.

Nuclear theft and sabotage risks may be initially compared by examining the maximum adverse consequences that have been associated with such events (Table 6.4). These consequences are upper-bounded by the potential effects of theft with intent to fabricate nuclear explosives. The United States currently faces risks, unrelated to commercial nuclear power, that have similar potential to produce adverse social consequences; e.g., theft of weapons from military installations, or theft of SNM from laboratories, etc. It is important to recognize that to quantify risk, outcome likelihoods must also be estimated in addition to outcome magnitude in order to realistically compare alternative fuel cycle options.

To quantify the likelihood that acts of nuclear theft or sabotage will succeed, event trees are constructed to describe credible event sequences that potentially lead to successful acts. These sequences can be divided into three categories:

- (i) Pre-Initiation Events: Those events that *precede* an act of nuclear theft or sabotage; e.g., gaining technical information, organizing the attack group, acquiring necessary equipment, formation of plans, choice of target and selection of goal, etc.,
- (ii) Initiation Events: Those events that *constitute* the actual act of nuclear theft or sabotage; e.g., entry to site, entry to facility, overcoming guards, disconnecting alarms, detonation of explosive at site, attack on transportation vehicle, etc., and
- (iii) Post-Initiation Events: Those events that take place *after* a

⁵Nuclear materials for weapons production include weapons grade plutonium, and highly enriched uranium (20% U-235/U-233 or greater). Reactor grade plutonium may also be used to produce nuclear explosives [90]. Such materials are given the designation "Special Nuclear Materials" (SNM) or "Strategic Special Nuclear Materials" (SSNM).

Table 6.4

COMPARATIVE THEFT-SABOTAGE RISKS

Commercial Nuclear Fuel Cycle Risks	Maximum Credible Adverse Effect	Risks U.S. Faces Today Unrelated to Commercial Nuclear Fuel Cycle*
<u>Theft</u> : Detonation of nuclear explosive made with SNM stolen from commercial nuclear facility.	Physical Destruction of Metropolitan Area	<u>Theft</u> : Detonation of nuclear explosive stolen from military installation or made with SNM stolen from military nuclear facility.
<u>Theft</u> : Dispersal of nuclear toxins stolen from commercial nuclear facility.	Massive Fatalities in Urban Area	<u>Theft</u> : Dispersal of non-nuclear toxins stolen from industry (e.g., cyanide, lead, mercury), super-toxins (e.g., botulinus), or nuclear toxins stolen from military nuclear facility.
<u>Theft</u> : Theft of nuclear material from commercial nuclear facility to extort demands or otherwise blackmail government.	Major Instability of Government	<u>Theft</u> : Theft of nuclear weapons or material from military installations to extort demands or otherwise blackmail government.
<u>Sabotage</u> : Physical damage to or initiation of accident in commercial nuclear facility.	Approximated by Maximum Credible Accident in Respective Facilities	<u>Sabotage</u> : Physical damage to or initiation of accident in non-nuclear industrial facility (e.g., natural gas storage tanks, toxic chemical plants, etc.), or in military nuclear facility.

* Exhibits only partial list of such risks.

successful theft of SNM; e.g., dispersal of toxins, processing of material for use in explosives, extortionist demands, etc.

Of the three initiation event categories, the first is the most difficult to assess, since little historical data or relevant experience is available to confirm probability estimates. However, insight can be gained by examining past events and the characteristics of these events with respect to group size, motive, level of armaments, etc. Information of this type is used in assigning prior distributions on pre-initiation events.⁶

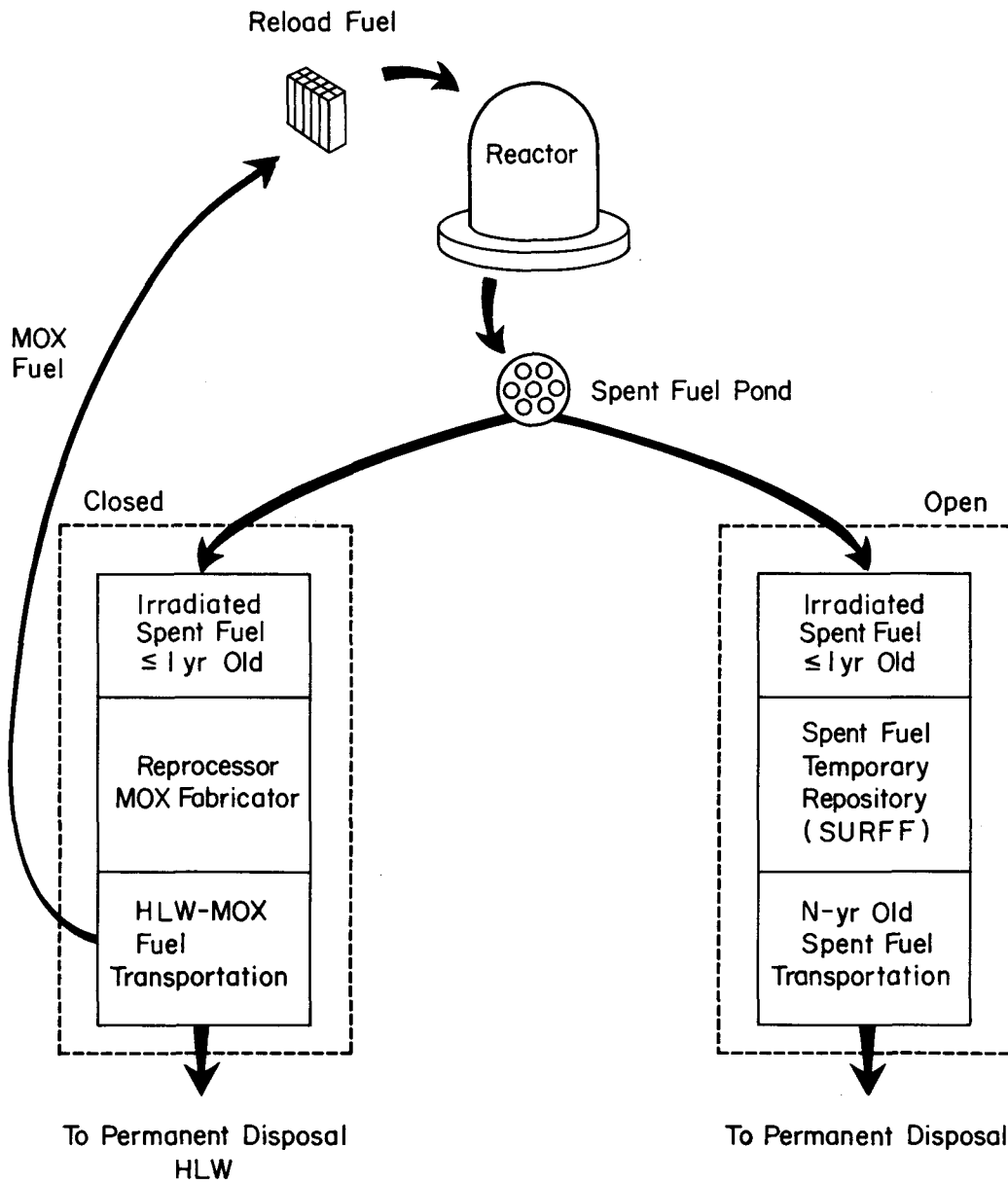
The second and third category of events lend themselves to direct assessment on the basis of technical experience related to such events; e.g., the likelihood of manufacturing a crude weapon in days, weeks, or months, or the likely yield of such a device, etc. Moreover, in analyzing the success likelihood of initiation events, methods for assessing safeguard system effectiveness are directly applicable. In this work, estimates on initiation event likelihoods follow the preliminary results of such safeguard studies.⁷

Previous studies of nuclear theft and sabotage risks have concentrated primarily on plutonium risks associated with the operation of the closed fuel cycle [4,91,92]. Comparatively little attention has been paid to the risks associated with the open cycle. Differences between open and closed fuel cycles as they affect domestic theft and sabotage risk are: (i) Reprocessor/MOX Fabricator versus Spent Fuel Temporary Repository (SURFF), and (ii) Fresh MOX Fuel Transportation versus HLW and N-yr

⁶For this purpose, a comprehensive data base related to terrorist and saboteur activity has been referred to, developed by the BDM Corporation and included in their report "Analysis of the Terrorist Threat to the Commercial Nuclear Industry" [93]. (Details are provided in Appendix D).

⁷Safeguard systems perform three functions according to the type of barrier that is presented to the would-be antagonist: (i) Deterrence -- the degree of discouragement the measure represents to the antagonist, (ii) Containment -- the reduction in success probability achieved by the system, and (iii) Recoverability -- the ability to prevent misuse of stolen SNM. Barriers that fall under these categories include two types: (i) Physical Security -- measures taken to physically prevent malevolence, and (ii) Technical -- materials measurement and accountability methods to render the material more difficult to steal or misuse.

Figure 6.4 Differences Between Closed vs. Open Fuel Cycles as They Affect Domestic Theft and Sabotage Risks



Old Irradiated UO_2 Spent Fuel Transportation (Figure 6.4). In the following sections, these two categories are examined and compared.

(i) Reprocessor-MOX Fabricator vs. Spent Fuel Temporary Repository

Much has been written about the potential for adverse social consequences resulting from nuclear theft or sabotage in commercial reprocessors and MOX fuel fabricators (e.g., Willrich and Taylor [4]). Comparatively little concern has been given to the possibility for theft of N-year old spent fuel from temporary repositories on the assumption that: "significant quantities of fission explosive materials [are not encountered] in forms that might be vulnerable to theft" (p. 36, [4]). However, a successful theft of significant amounts of N-year old spent fuel presents the potential for adverse social consequences similar to that from the theft of materials from a reprocessor-MOX fabrication facility.

In a reprocessor-MOX fabricator, there are four materials that are considered vulnerable to theft: (i) plutonium nitrate in solution form, (ii) plutonium oxide in powder form, (iii) MOX fuel pellets, and (iv) MOX fuel in single rod or assembly form. The advantage of diverting either of the first two materials is that the plutonium exists in a relatively purified form, while MOX fuel would need be reprocessed by the terrorists to extract the plutonium oxide.

Differences between N-year old spent fuel and MOX fresh fuel relate to their relative plutonium oxide content, radiation and thermal output, and material toxicity (Table 6.5). Although fresh MOX fuel offers the greater advantage as a source of nuclear explosive material because of its four to five time greater plutonium oxide content and lower handling hazard, spent fuel has a significant advantage as a material for direct dispersal purposes or use in dispersal weapons because of its higher toxicity index. Thus, it is important to examine the possibility for theft in both open and closed fuel cycle alternatives.

In assessing these comparative risks, it is assumed that the reprocessor is co-located with the MOX fabricator so that no separated plutonium need be

Table 6.5

RELEVANT ATTRIBUTES OF FRESH MOX FUEL AND 10-YEAR OLD UO₂ SPENT FUEL

Attribute	Fresh MOX Fuel	10-year Old Spent Fuel
Plutonium Oxide Content PuO ₂ per Assembly (kg)	4-5% by Weight PWR: 21-26 BWR: 9-11	.6-1% by Weight PWR: 3.1-5.2 BWR: 1.3-2.2
Potential Explosives per Assembly-- Packed PuO ₂ ^{a/}	PWR: .5-.7 BWR: .2-.3	PWR: .1-.13 BWR: .03-.06
Maximum Gamma Radiation Hazard per Fuel Rod (PWR) ^{b,c/} (REM/hr)	Negligible	145 @ 1 foot (30 cm) 33 @ 3 feet (1 m) 2 @ 16 feet (5 m)
Relative Toxicity Index per MT-Fuel (m ³ Air; Water) ^{d/}	H ₂ O 1.5 x 10 ⁶ Air 1	H ₂ O 3.10 x 10 ⁷ Air 2.0 x 10 ¹⁰
Thermal Output Per Rod Temperature Outside Cladding	Negligible Equal to Temperature of Surroundings	.5 watt or .04 $\frac{\text{watt}}{\text{foot}}$ Equal to Temperature of Surroundings

^{a/} Assumes 40 kg PuO₂ required per explosive (Selden, [90]).

^{b/} Threshold of detectable clinical effects is 5-25 REM, with nausea and fatigue appearing between 100-200 REM. At 450 REM, half the population exposed would die within 30 days. Most γ radiation in fresh MOX fuel is from Pu-241. Given a Pu-241 content in fresh MOX equal to that in UO₂ spent fuel, the dose is ~.1 m REM/hour @ 1 foot (30 cm), or 1.5 million times less than the dose from 10-year old spent fuel.

^{c/} Compared to 30-day old spent fuel, the dose @ 30 cm is ~17 x 10³ REM/hour, or about 100 times greater than that for 10-year old spent fuel. Neutron dose for spent fuel @ 10-years is negligible compared with gamma-contribution.

^{d/} Relative toxicity index with respect to U-238 (U-238 = 1) for contamination of water. Sr-90 and Cs-137, -134 contribute most to spent fuel toxicity in water, with Kr-85 (gas) contributing most to toxicity in air.

transferred off the facility site.⁸ The two processes are considered housed in a single hardened complex protected by the same physical safeguard system (Figure 6.5).⁹ It is further assumed that the fabricator is sized to fit the reprocessor capacity of 1500 MTU/yr. The reprocessor is thought to operate using the PUREX process, and subsequent plutonium nitrate conversion to plutonium oxide is performed using a process that permits the direct transfer of the material to the fabricator without a storage step required (e.g., Sol-Gel process).¹⁰ The reprocessor separates the spent fuel into recoverable uranium, plutonium, and high-level waste streams. The HLW is solidified, converted into an insoluble form and then shipped to the permanent HLW repository. The recovered uranium is shipped after conversion to an enrichment plant, or used directly as input to the MOX fabricator.

For comparative purposes, the spent fuel temporary repository is considered to handle 1500 MT spent fuel/year, which is then transported to a remotely located permanent spent fuel repository after being stored for N years (assumed as 10 years in this study) (Figure 6.6). The facility is assumed physically safeguarded using the same precautions as in the reprocessor-MOX fabricator case.¹¹

⁸Co-location is assumed based on two observations: (i) current regulations require that plutonium be placed into a solid form prior to shipment for safety reasons (10-CFR-71.42), and (ii) further regulation development may likely require co-location mandatory for safeguards reasons [94]. The APS notes that such regulation may create commercial problems at the outset of the industry in that different companies would have to operate as closely-coupled partners. However, the APS sees no insurmountable obstacles to overcoming such problems [81]. The Atomic Industrial Forum (AIF) also sees similar problems, but is not opposed to the idea [95].

⁹This concept follows after a design being proposed on the basis of safeguard considerations by du Pont at Savannah River [96,97].

¹⁰Other concepts, such as co-processing variants, have not been considered. These concepts may reduce safeguards risks, but affect the economics of reprocessing as well [98,99]. Therefore, the discussion has been restricted to variants of the PUREX process for which the economics are better understood.

¹¹The physical safeguard system described by E.R. Johnson and Associates is considered in this study, representing an exemplary system providing maximum security at a site handling plutonium [100].

Figure 6.5 Conceptual Rep/MOX Facility

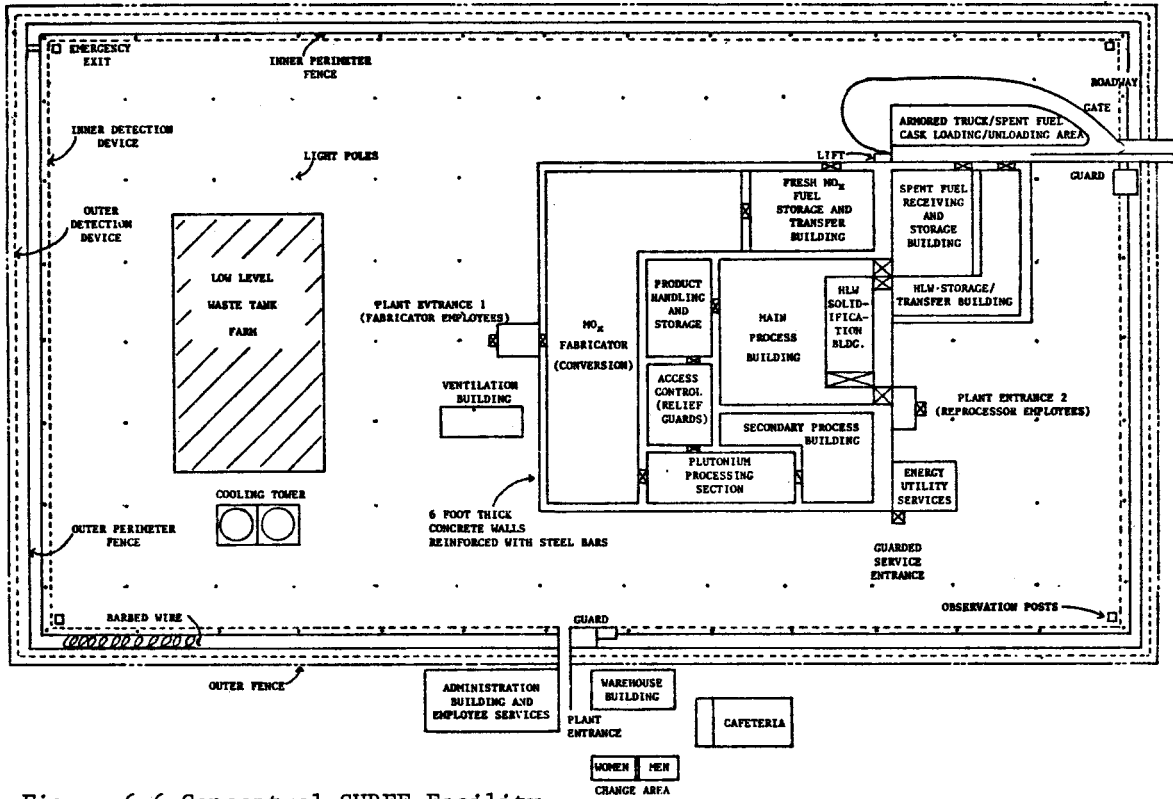
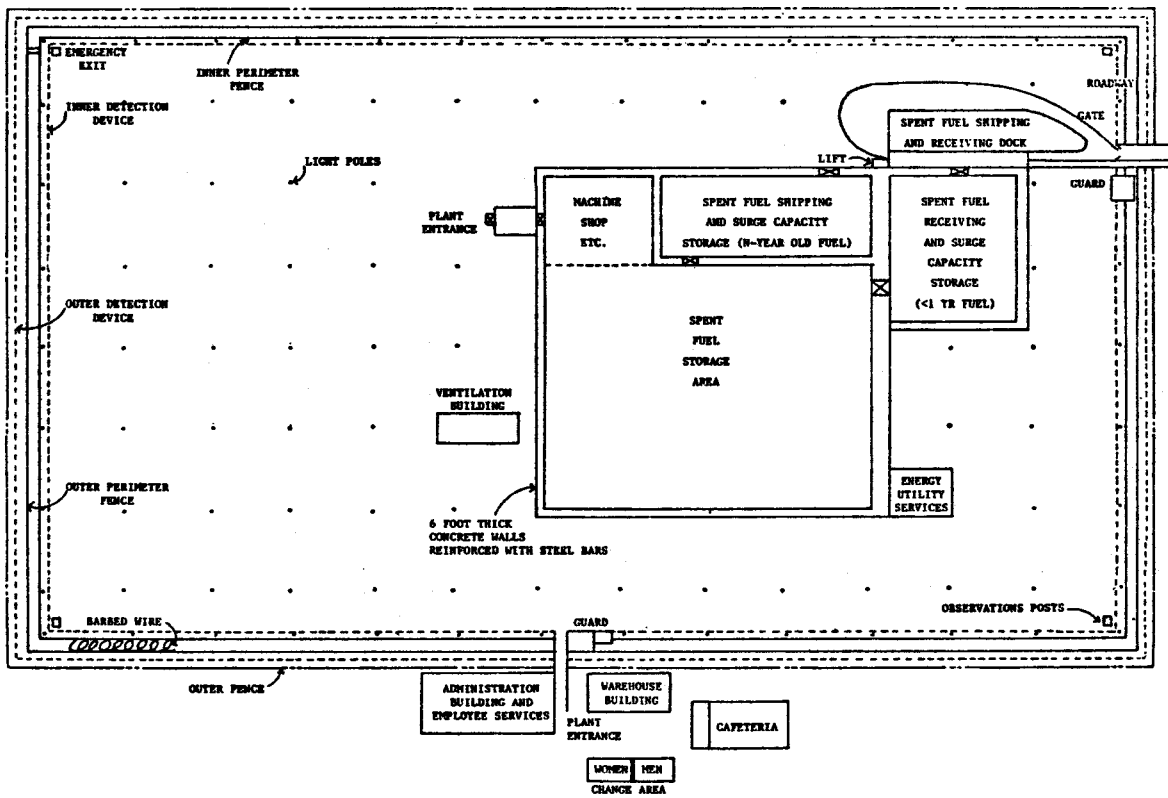


Figure 6.6 Conceptual SURFF Facility



Risks examined include two categories of sabotage attempts: (i) the case where a disgruntled employee (or employees) and/or armed group would attempt to cause financial loss at a facility by damaging expensive equipment through use of appropriate tools or explosives, and (ii) the case where a disgruntled employee (or employees) and/or armed group would attempt to cause a significant radiation release from the facility by initiation of a serious accident, either through the use of appropriate tools or explosives. Three categories of nuclear theft attempts were examined: (i) the case where a disgruntled employee (or employees) and/or armed terrorist group would takeover the facility threatening to do damage to it while holding hostages so as to extort demands from society, (ii) the case where a disgruntled employee (or employees) and/or armed terrorist group would enter the facility and steal material for use in dispersal weapons, and (iii) the case where a disgruntled employee (or employees) and/or armed terrorist group would enter the facility and steal material for use in nuclear explosives. Differences in risks between the two facilities were assessed through the use of representative event trees (see App. D). On the basis of this assessment, differential nuclear theft and sabotage social costs between open and closed fuel cycle alternatives are estimated to range between 76-242 \$/GWe-year.

(ii) Transportation of Fresh MOX Fuel vs. N-Year Old Spent Fuel

The second major difference between open and closed fuel cycle alternatives is the transportation of fuel between facilities; in the closed cycle case, the fresh MOX fuel must be transported back to the reactors, while in the open cycle case, N-year old spent fuel must be transported to its permanent burial grounds. Risks examined include two sabotage cases: (i) the case where a disgruntled employee or armed group would cause a financial loss by damaging a fuel transport vehicle while it awaited use at a storage facility, either through use of an explosive or appropriate tools, and (ii) the case where a disgruntled employee or armed group place a timed explosive on the transport vehicle prior to shipment causing an explosion during shipment resulting in dispersal of materials to the environment and injury or death of occupational personnel involved. Three theft scenarios were considered: (i) the case where armed terrorists/employees

attempt to takeover the material while in transit between facilities for extortion purposes, (ii) the case where armed terrorists takeover a shipment while it is in transit stealing the material for use in a dispersal weapon, and (iii) the case where armed terrorists takeover a shipment while in transit stealing the material for use in nuclear explosives.

A risk assessment is carried out under the assumption that both fuel types would be transported using the same safeguard and transport procedures [100]:

- (i) A national radio network system for providing two-way communication with all vehicles transporting fuel at any time and any place in the United States,
- (ii) A recovery force of ~80 men to respond immediately to any attempted theft during shipment,
- (iii) A command center at one of the radio network system stations which would exercise control over both the radio network and the recovery force, and would be responsible for coordinating support from the military, the FBI, and other law enforcement agencies,
- (iv) A single type of container for the shipment of MOX or N-year old spent UO_2 fuel assemblies,
- (v) Special trucks designed for the shipment of MOX or N-year old spent UO_2 fuel assemblies dedicated for use only in such shipments, and
- (vi) All shipments accompanied by armed guards in two escort vehicles.

In addition, the drivers and escort vehicles would have access to remotely controlled switches that activate devices to incapacitate the vehicle carrying the fuel so that access to the vehicle in its operational state could not take place. This precaution decreases the likelihood that terrorists could overcome the vehicles' drivers and drive away with the material.

The sequence of events necessary to overcome the safeguard system is assumed the same between the two categories of fuel (see App. D). However, the ease by which the plutonium can be extracted from each fuel form and the relative amounts extractable differ between categories.

Results of the risk assessment indicate that sabotage with intent to

cause financial loss dominates the nuclear theft risk. Assuming that both fresh MOX fuel and N-year old spent fuel will be transported using similar vehicles, the differential nuclear theft and sabotage social costs between the transportation of the two fuel types is negligible, as the major financial loss is assumed to occur as a result of damage to the unloaded transport vehicle.

C. Comparision of Domestic Technological Risks

Nuclear theft and sabotage risks appear to be dominated by health, environmental, and safety risks, with occupational health risks from routine radiation release contributing the largest amount to the total social costs (Table 6.6). The health, environmental and safety estimates reflect a range of 30-100 \$ per Person-REM assigned to low level radiation health effects. The range on nuclear theft and sabotage social costs reflect assumptions made on event likelihoods and outcome values (see Appendix D).

Table 6.6

EXPECTED VALUE SOCIAL COSTS -- OPEN VS. CLOSED CYCLES*
(In mills/kWh @ 60% Capacity Factor; 1975 \$)

	Health, Environmental, and Safety	Nuclear Theft and Sabotage
Open	.001 -- .03	.000017 -- .000029
Closed	.001 -- .03	.000042 -- .00006

*To convert to \$/GWe-year, multiply mills/kWh by
 $\sim 5.53 \times 10^6$

These conclusions indicate the difficulty of making a reliable decision on the basis of discernible differences in domestic social costs between open and closed fuel cycle alternatives. Thus, the fact that, by closing the fuel cycle, a major decrease in routine radiation released to the environment occurs because of the decrease in mining and milling in the front-end of the fuel cycle would seem to compensate for whatever increase in risk results from nuclear theft or sabotage considerations.

Chapter 7

SOCIAL COSTS DUE TO THE RISK OF NUCLEAR PROLIFERATION

Atoms for Peace -- *or war?*

-- John A. Hall [101]

Overview

This chapter examines the impact of the U. S. reprocessing decision on the risk of nuclear proliferation^{1,2}. First, the range of expert opinion concerning both the effects of nuclear proliferation and its relationship to commercial nuclear power are outlined (Section A). Then a decision model is constructed and a policy-region diagram derived that incorporate the range of expert opinion (Section B). The magnitude of proliferation risk is then estimated by defining a "value-of-non-proliferation" (v_p) and examining available technological routes to weapons material attainment (Section C).

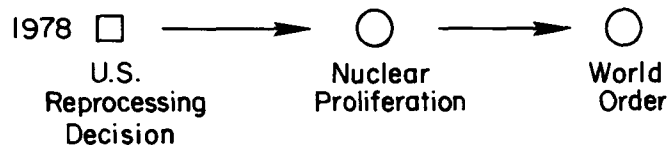
¹Nuclear proliferation is defined as the acquisition, development, and demonstration of nuclear weapons capability by a former Non-Weapons State (NWS). The NWS thus becomes a weapons state, such as the six countries which currently (as of 1978) have demonstrated a nuclear capability (i.e., the U.S., U.S.S.R., U.K., France, People's Republic of China, and India).

²This chapter presents a treatment of the proliferation issue using standard methods of formal decision analysis. A separate but related analysis of the problem using the methodology of influence diagrams is presented in Appendix E.4.

A. Effects of Nuclear Proliferation/Relationship to Commercial Nuclear Power

To first order, the influence of the reprocessing decision on nuclear proliferation and the influence of nuclear proliferation events on world order can be related as follows (Figure 7.1).

Figure 7.1 First-Order Influence Diagram



Expert opinion concerning the impact (or influence) of proliferation events on world order is varied and diverse, but can be classified into three principal viewpoints³: (i) Effects Are Large and Adverse, i.e., proliferation produces large adverse effects on world order; (ii) Effects Are Negligible, i.e., proliferation produces little or no effect on world order; and (iii) Effects Are Beneficial, i.e., proliferation produces positive, beneficial effects on world order. Only under the first viewpoint is proliferation considered undesirable; it is the only perspective under which future events of proliferation are considered to imply social risk.

Equally varied and diverse are expert opinions concerning the influence of the U.S. reprocessing decision on future nuclear proliferation events (see Appendix E.1.2). Three principal viewpoints have been identified:

- The effect of permitting reprocessing would be to substantially increase both the number and rate of future proliferation events; i.e., the U.S. reprocessing decision is closely coupled to similar decisions facing NWSs, and commercial reprocessing is an attractive

³Detailed descriptions and documentation of these viewpoints are provided in Appendix E.1.1.

route whereby NWSs can easily acquire, through covert or overt diversion, weapons-usable material;

- The effect of the reprocessing decision on proliferation is negligible; i.e., whatever option is chosen, the U.S. reprocessing decision does not influence the decision by NWSs to acquire nuclear weapons, and is further decoupled from proliferation because commercial reprocessing is a highly unattractive route in comparison to other non-commercial routes by which to acquire weapons material; and
- The effect of a "permit" decision is to decrease the number and rate of proliferation events; i.e., although the U.S. reprocessing decision may or may not be coupled to similar decisions facing NWSs, it is the spent fuel stored alongside power reactors inside NWSs that represents the more attractive route to weapons-usable material as the construction and operation of a clandestine reprocessing facility is relatively easy. An "open" cycle policy of the U.S. encourages NWSs to develop indigenous reprocessing capacity potentially free from international safeguards.

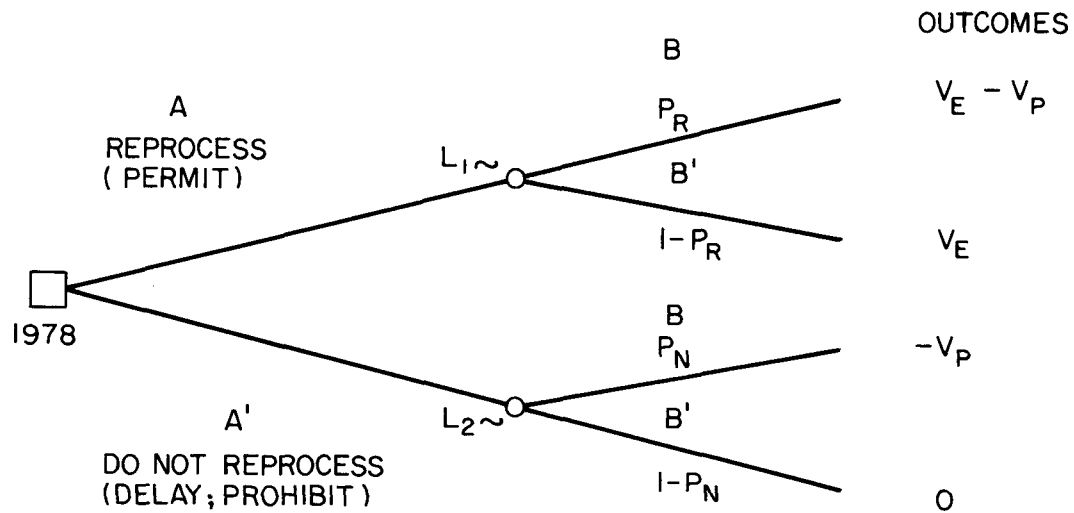
B. Extended Decision Model

Inclusive of proliferation, the U.S. reprocessing decision can be summarized as the choice between two lotteries (Figure 7.2), where P_R is the probability proliferation occurs *with* reprocessing, P_N the probability proliferation occurs *without* reprocessing, v_E the economic value of reprocessing (both direct and indirect benefits), and v_p the value of non-proliferation. This simple model indicates how the decision rests on the change in probability of proliferation, denoted $\Delta (= P_R - P_N)$, when reprocessing is permitted vs. prohibited or delayed.

To calculate the breakeven curve, resulting in a policy-region diagram, it is assumed that society satisfies the delta property (see ref. [102]), which implies society implicitly uses either a linear utility function (equivalent to saying society acts as an expected value decision maker⁴) or exponential utility function reflecting risk aversion. Analyzing the

⁴This is equivalent to assuming that the assignment of a numerical value to v_p is independent of the derived value for v_E , and that the value of the joint occurrence of A and B' is just their sum [103].

Figure 7.2 U.S. Reprocessing Decision Inclusive of Proliferation*



* v_E = Annualized Differential Benefits between Permit and Delay (or Prohibit). Further, v_p = Annualized Value of Non-Proliferation to U. S. Society; P_R = Probability of Proliferation with Reprocessing; P_N = Probability of Proliferation without Reprocessing, where the probability of proliferation is defined as the likelihood that one additional country acquires nuclear weaponry within a given year; L_1 and L_2 denote lotteries and A,A',B,B' denote events.

decision on an expected value basis⁵, the decision to permit reprocessing is rational (according to the axioms of logic [102]) if lottery L_1 is preferred to lottery L_2 (i.e., $L_1 > L_2$). This is the case if the following inequality holds true:

$$(1 - P_R) \cdot (v_E) + P_R \cdot (v_E - v_P) > P_N \cdot (-v_P)$$

$$v_E - (P_R \cdot v_P) > P_N \cdot (-v_P)$$

$$v_E > (P_R - P_N) \cdot v_P$$

or

$$v_E > \Delta \cdot v_P$$

The "break-even" curve, $v_E = \Delta \cdot v_P$, represents a rectangular hyperbola, as is indicated in the resulting policy-region diagram (Figure 7.3).

C. The Magnitude of the Risk

Having established the general decision framework, it is now necessary to examine the value of non-proliferation in order to establish a quantitative estimate for Δ , the differential likelihood of proliferation between decision options. This estimate can then be compared to the value for Δ derived through a quantitative comparison of alternative routes to weapons-material attainment. In this way, the relative magnitude of proliferation risk between decision options can be compared.

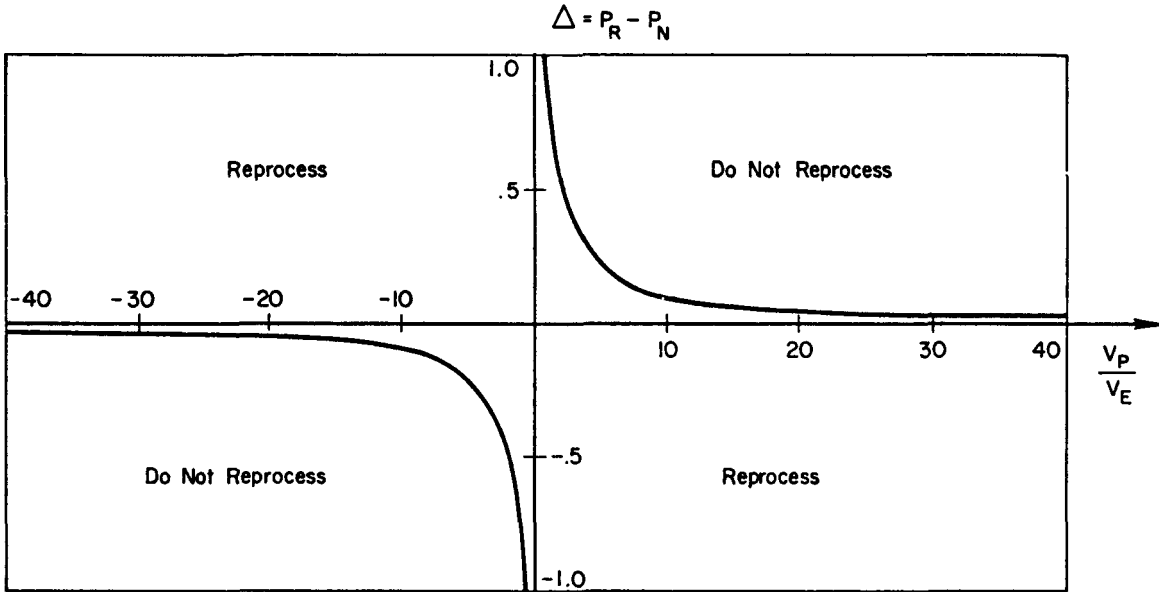
(i) The Value of Non-Proliferation

Two perspectives can be used to assess v_P : (i) that of *society* as a whole, asking how much the U.S. is willing to pay to reduce the risk of nuclear proliferation, and (ii) that of an *individual* member of society, asking how much of an increase in risk an individual is willing to accept

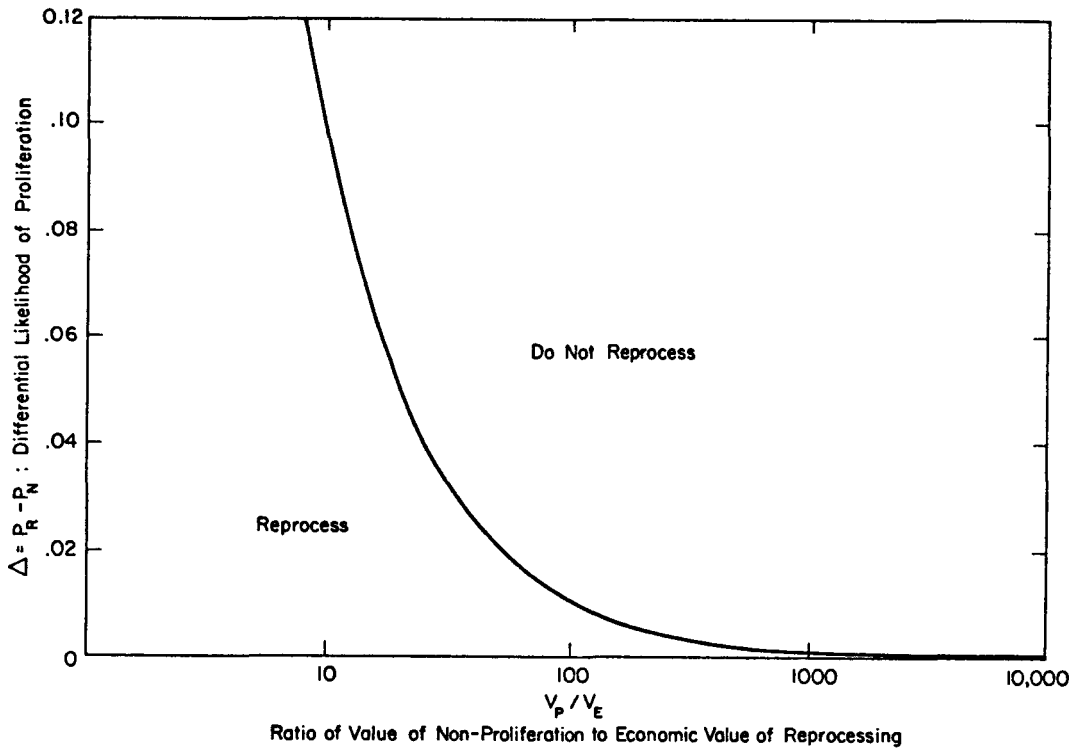
⁵It was noted (see Chapter 1) that analyzing social decisions on an expected value basis is appropriate when the outcomes of a decision (in this case, v_E and v_P) are small in comparison to the GNP for the overall economy.^E While this is clearly the case for v_E based on earlier results, it is not as yet evident for v_P .

Figure 7.3 Resulting Policy-Region Diagram for U.S. Reprocessing Decision

a. Policy-Region Diagram: "Break-Even" Curve Rectangular Hyperbola



b. Expanded Scale



given that he is compensated over his lifetime by an annuity equivalent to reprocessing economic benefits (Table 7.1).

Table 7.1

PERSPECTIVES ON THE VALUE OF NON-PROLIFERATION

Society As a Whole: How much is the United States as a society *willing to pay to reduce* proliferation risk?

Individual Member of Society: How much of an increase in risk is the individual *willing to accept* given that he is compensated by an annuity equivalent to per capita reprocessing economic benefits (reflected in individual's electricity bill)?

Using the first perspective, it is possible to place a quantitative bound on v_p by recognizing that the U.S. cannot afford to spend more than its annual gross national product (GNP) of two trillion dollars per year (as of 1978) to reduce proliferation risk⁶. A more reasonable upper bound might be established by determining what U.S. society currently pays to reduce risks associated with an already proliferated world.

One approach is to use increments in the defense budget that would result from proliferation as a measure of the worth of non-proliferation. This approach considers U.S. defense spending in response to a nation-by-nation demonstrated weapons capability; i.e., how much should U.S. society be willing to pay now to avoid later defense expenditures? It can then be assumed that yearly expenditures to defend the U.S. against emerging weapons states is upper bounded by the current annual national defense budget of ~ 112 billion dollars (1975 \$ terms), which reflects

⁶The value v_p is not to be mistaken as the dollar value placed on any particular effect associated with nuclear proliferation (e.g., nuclear war). Instead, v_p should be thought of as the certain equivalent of the lottery representing possible proliferation effects. Note that assuming a positive value for v_p reflects a bias toward the viewpoint of those who believe that proliferation effects are large and adverse (see 7.A and Appendix E.1.1).

Table 7.2

DEFENSE DEPARTMENT EXPENDITURES

A. Classification of Expenditures [104]

The current Defense Department annual budget of 112 billion dollars (as of 1978) can be divided into nuclear and non-nuclear related expenditures:

- | | |
|---|---|
| <p>1. <u>Non-Nuclear Related Expenditures:</u>
 Funds general-purpose forces, guard and reserve, central supply and maintenance, training/medical and other general personnel activities, administration.</p> | <p>73% of budget
 or 82 billion dollars</p> |
| <p>2. <u>Nuclear Related Expenditures:</u>
 Strategic forces, intelligence and communications, airlift and sealift, research and development, support of other nations.</p> | <p>27% of budget
 or 30 billion dollars</p> |
| <p><u>Atomic Energy Defense Activities:</u>
 (Research at LLL and IASL, Nevada Test Site)</p> | <p>2.2 billion dollars
 out of nuclear related expenditures</p> |
-

B. Defense Spending as a Percentage of National GNP [103]
 (Data from 1976 Statistical Abstract)

<u>Year</u>	<u>%GNP*</u>	<u>%GNP (Total)</u>		<u>Year</u>	<u>%GNP*</u>	<u>%GNP (Total)</u>
1950	4.7	4.7		1970	6.48	8.3
1955	10.5	10.5		1971	6.38	7.5
1960	9.1	9.1	$\bar{X} = 6.24$	1972	6.35	7.0
1965	7.38	7.4	$\bar{X} = .49$	1973	5.67	6.1
1967	6.53	8.9	for 1967-	1974	5.60	5.8
1968	7.18	9.6	1976	1975	5.92	6.0
1969	6.51	8.9		1976	5.78	5.8

* Values from 1965 through 1976 are adjusted to remove incremental costs of Southeast Asian war.

current expenditures necessary to defend the country against the present proliferated world.⁷

To further establish a range on v_p , defense department expenditures were examined (Table 7.2). Defense spending for the year 1978 was classified into two categories: nuclear and non-nuclear expenditures, where nuclear expenditures represent 27% of the budget, or 30 billion dollars per year. A reasonable lower bound on v_p might represent 1% of the total defense budget, or ~ 1 billion dollars per year, while a reasonable upper bound might represent a 100% increase in defense spending per year, or ~ 100 billion dollars per year. These bounds correspond to hypothetical yearly tax increases of from 20 to 2000 dollars per average American family.

To determine where in this range v_p might be expected to fall, U.S. response to past events of proliferation was examined (Table 7.2B); for example, to the Indian detonation of 1973. Historical response indicates a yearly increase in the defense budget of some 6% per year, or roughly 6 billion dollars per year. It can be expected that changes in the rate of proliferation events would be reflected in an increase or decrease of this expenditure, also in response to which country proliferates and when. To establish an estimate for v_p , future rates of proliferation are assumed greater than the historical rate, corresponding to annual expenditures of $\sim 10\%$ of the 1978 defense budget, or 12 billion dollars per year. Alternatively, this value corresponds to a hypothetical increase in taxes of 240 dollars per year for the average American family.

In order to derive a range on Δ as a function of v_p , the economic value of reprocessing v_E calculated earlier in Chapters 4-5 is used:

$$v_E = v_E^D + v_E^I$$

Total Economic Value	=	Direct Economic Benefits	+	Indirect Economic Benefits
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which, @ 6% in 1975 billions of dollars over the time span 1975-2050, were calculated in expected value terms as follows:

Permit:	81.9	=	10.0	+	71.9
Delay:	41.7	=	3.1	+	38.6
Prohibit:	0				

⁷This approach implies that the value of non-proliferation to the U.S. varies as a function of which country proliferates; i.e., in the case of allies and other countries with close ties to the U.S., v_p might actually assume a negative value.

with differential benefits between Permit and Delay options of 40.2 billion dollars.

This value is converted from PV terms into an annuity by applying an appropriate capital recovery factor A/P (which is $\sim .0608$ for a SDR of 6% over the 75 years represented by the study time-span of 1975-2050). Thus, for Permit vs. Delay decision options, $v_E \approx 4.02 \times 10^{10} \times .0608 \approx 2.45 \times 10^9$ dollars (1975 terms). Using the representative value for v_P of 12×10^9 dollars, an estimate for Δ of $\sim 20\%$ results (Figure 7.4).

Figure 7.4 Estimation of Differential Likelihood Δ for Permit vs. Delay Reprocessing Decision Options

Given a value of non-proliferation of $v_P = 12 \times 10^9$ \$/yr, Delay is optimal over Permit if:

$$\Delta > \frac{v_E}{v_P} \Big|_{\text{annualized basis}} = \frac{(A/P, 75 \text{ years, } 6\%) (v_E^{\text{Permit}} - v_E^{\text{Delay}})}{v_P \Big|_{\text{annualized basis}}}$$

or

$$\Delta > \frac{(.0608)(40.2 \times 10^9 \$)}{(12 \times 10^9 \$)} = \frac{2.45 \times 10^9}{12 \times 10^9}$$

$$\Delta \gtrsim 20\% \quad (\text{representative value})$$

Thus, treating the decision in expected value terms, while using a representative value of non-proliferation v_P of ~ 12 billion \$/year, the change in the likelihood of nuclear proliferation between permit and delay options would need to be at least 20% before delay would become the preferred alternative.

(ii) Routes to Weapons-Material Attainment

In order to derive a quantitative value for Δ , two areas need be examined:

- the relative attractiveness of available routes to weapons-material attainment, comparing the relative advantages an open or closed fuel cycle implies for weapons purposes against other routes, and
- comparing the relative advantages between an open and closed fuel cycle.

Quantitative rankings representing the relative attractiveness of available routes can be established by comparing attributes of each system with others. A list of important attributes is provided in Table 7.3.

Table 7.3

MULTI-ATTRIBUTES ASSOCIATED WITH AVAILABLE ROUTES
TO WEAPONS-MATERIAL ATTAINMENT

1. Domestic Availability of Technology
 2. Import Availability
 3. Capital, Operating, and Maintenance Costs
 4. Suitability for Clandestine Operation
 5. Difficulty of Technical Implementation
 6. Number of Weapons Attainable
 7. Quality of Weapons Material
 8. Number of Technical Personnel Required
 9. Level of Support Technology and Industry Required
 10. Time Required to Construct Facility
-

The contribution that commercial reprocessing represents to proliferation risk may be estimated by comparing the relative advantages reprocessing offers over some eight currently identified routes to weapons material attainment (Table 7.4). Research reactors (which over 50 countries now own and operate) and production reactors, when coupled to minimum plutonium-recovery plants (MPRPs)⁸, can be used to obtain weapons

⁸A description of the resource and technological requirements for the construction and operation of a MPRP is found in an ORNL study by D. E. Ferguson [107].

Table 7.4

ROUTES LEADING TO WEAPONS MATERIAL ATTAINMENT [12,105-106]

I. 1978: Nine Routes Available:

Reactor/Reprocessor Route (Pu for weapon):

1. Research reactor (natural U or enriched U) } Coupled to minimum
2. Production reactor (natural U) } plutonium-recovery plant
3. Power reactor (natural U or enriched U) coupled to MPRP
4. Power reactor (natural U or enriched U) coupled to commercial reprocessor

Enrichment Technologies (U for weapon):

5. Diffusion cascade
6. Centrifuge
7. Aerodynamic jet cascade
8. Electromagnetic separation

Neutron Generator:

9. Accelerator

II. 1980's-1990's: Seven Additional Routes:

Enrichment Technologies (U for weapon):

1. Laser isotope separation (1982 +)
2. Chemical exchange isotope separation (?)
3. Jet membrane isotope separation (1984 +)

Neutron Generators:

4. Plasma fusion-fission (Tokomak) (2000 +)
5. Inertial fusion-fission: laser implosion/electron beam (2000 +)
6. Intense neutron generator accelerator (1980-1985)
7. Thermonuclear weapon design w/o fission trigger (198x)

material. Enrichment technologies are also routes to such a goal. In the future, seven other routes may become available, including laser isotope separation, chemical separation, and jet membrane enrichment techniques, and high-energy neutron sources such as the fusion Tokomak machine, fission-fusion systems, and the intense neutron generator accelerator.

The decision faced by the Nth country after it has decided to pursue the development of a nuclear weapons capability is to determine which route (or routes) available are to be used to attain weapons-usable material as a function of the scale of capability it desires (Fig. 7.5). (It can make the decision in stages, bringing it up to a matter of hrs/dys away.)

After carrying out an assessment of the relative attractiveness, import and domestic availability of the nine routes currently available to a non-weapons state, relative rankings were established (Table 7.5 -- details provided in Appendix E.2). These rankings indicate that the more attractive routes are those of the research and production reactors coupled to MPRPs, based on current domestic and import availability of research reactors, and the higher quality weapons-grade material attainable from a suitably operated production reactor. Correspondingly, the spent fuel from a power reactor is attractive for diversion to a clandestinely operated MPRP, since commercial reprocessors are less available on an import basis than are power reactors⁹, and MPRPs are less difficult to build than are commercial reprocessing facilities.

The relative rankings on available routes to weapons material attainment provide rough estimates on the differential likelihood of proliferation Δ between reprocessing decision options¹⁰. The 3% ranking for the commercial reprocessor/power reactor route indicates the overall relative attractiveness of the route to a non-weapons state desiring a minimal weapons capability. Using the 3% figure as an estimate for Δ , and a value of non-proliferation v_p of 12 billion dollars per year, a factor

⁹If tight export regulations inclusive of international safeguards are not enforced on a worldwide basis, the relative ranking for the commercial reactor + reprocessor route could increase.

¹⁰A discussion of the effect of Nth country motivational factors on the estimate for Δ is provided in Appendix E.3.

Table 7.5

RANKINGS OF CURRENTLY AVAILABLE ROUTES TO WEAPONS MATERIAL ATTAINMENT

I	Route	R_I^A	R_I^D	R_I^I	Relative Ranking (%)
1	Res Reac (+MPRP) *	.192	.189	.27	32.1
2	Prod Reac (+MPRP)	.186	.3	.05	25.5
3	Power Reac (+MPRP)	.077	.075	.27	10.3
4	(Power Reac +)Com Rep*	.064	.075	.06	<u>3.4</u>
5	Diffusion Cascade	.071	.113	.1	5.9
6	Centrifuge Cascade	.115	.113	.1	9.5
7	Aerodynamic Jet	.102	.075	.1	7.0
8	Electromagnet Sep	.083	.04	.033	4.6
9	Accelerator	.110	.02	.017	1.6

$\Sigma = 1 \quad \Sigma = 1 \quad \Sigma = 1 \quad \Sigma = 100\%$

where

R_I^A = ranks the relative attractiveness of Option I on the basis of cost, technical difficulty, material flow, time to weapon, etc. (Data used to establish ranking provided from four studies; see Appendix E.2)

R_I^D = ranks the relative domestic availability of Option I to the Nth country on a technical basis. (Author's Rankings)

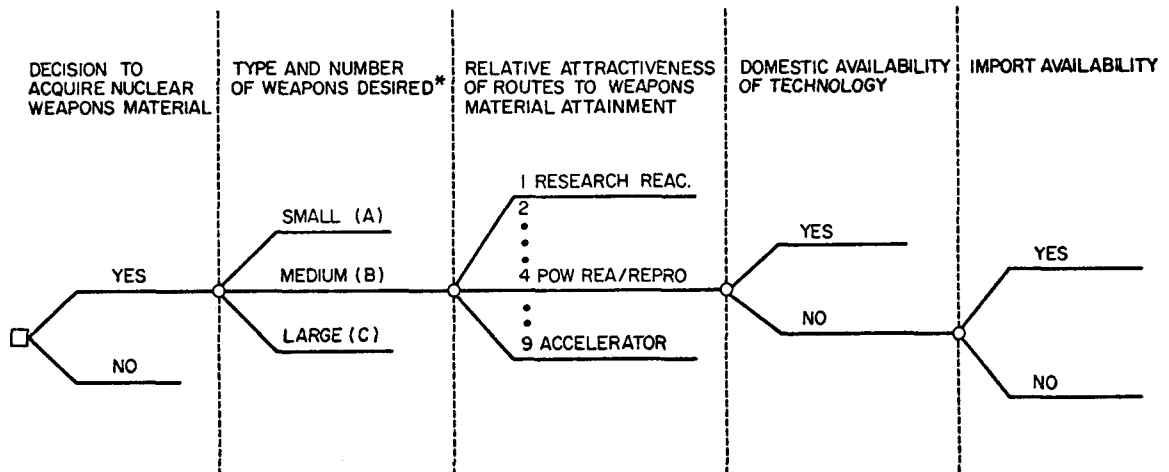
R_I^I = ranks the relative importability of Option I (or the market availability abroad). (Author's Rankings)

$$\text{Relative Ranking (\%)} = ((1-R_I^D) \cdot R_I^I + R_I^D) \cdot R_I^A \cdot (\text{Sum Rel. Rank.}_I)$$

* Assumes Minimum Plutonium Recovery Plant (MPRP) can be constructed by the Nth country without foreign assistance; rankings are estimates for reactors themselves except in the case of the power-reactor/commercial reprocessing route, where the ranking is for the reprocessor.

of ~ 6 between the benefits and costs of reprocessing is implied. That is, on the basis of these assumptions, the economic benefits foregone by delaying the reprocessing decision outweigh any benefits the U.S. derives on the basis of proliferation risk considerations by a factor of approximately six times.

Figure 7.5 Nth Country Decision to Acquire Nuclear Weapons Material



- *
 A= Small Scale Weapons Program to produce a few weapons for political rather than military purposes;
 B= Medium Scale Weapons Program to produce a military weapons program including the stockpile of weapons and development of nominal delivery capability;
 C= Large Scale Weapons Program on par with super powers to produce highly sophisticated A and H bombs with accompanying delivery capability inclusive of missiles, submarines, bombers, command posts, etc.

Chapter 8

STUDY RESULTS

Decision Analysis is no more than a procedure for applying logic. The ultimate limitation of its applicability lies not in its ability to cope with problems but in man's desire to be logical.

--Howard [21]

Overview

This chapter reviews and places into perspective the results of previous chapters. The economic benefits calculated in Section III are compared with the domestic social costs calculated in Section IV. Policy implications of nuclear proliferation are described and general conclusions drawn.

A. Economic and Social Cost-Benefit Comparison

Both direct economic benefits due to the reprocessing of LWR spent fuel and the recycle of recovered products, and indirect economic benefits due to the implications of the reprocessing decision on LMFBR introduction dates, were estimated. A dynamic fuel-cycle simulation model driven by LWR capacity and reprocessing schedule information was developed to calculate direct benefits. A fuel substitution model based on an event tree description of possible electricity states-of-the-world was used to calculate indirect benefits. Results indicate that indirect benefits outweigh direct benefits by a substantial factor, and that the permit option dominates that of delay (Table 8.1). Further, post-2005 indirect benefits due to the breeder outweigh pre-2005 indirect benefits, as the LMFBR is not expected to be commercialized on a wide scale before the year 2005, regardless of the reprocessing decision option chosen. However, pre-2005 direct economic benefits dominate those accruing beyond the end of the century, reflecting prior assignments on the date of introduction of advanced energy technologies (AETs) and the LMFBR, both of which can be expected to limit the growth of, or act to replace, the LWR. These conclusions indicate the near- and long-term effects of a

Table 8.1

EXPECTED VALUE TOTAL ECONOMIC BENEFITS
(In Billions of 1975 Dollars (mills/kWh))

Decision Options	Social Discount Rate					
	0%			6%		
	Direct	Indirect	Total	Direct	Indirect	Total
Permit	65 (1.24)	1600 (30.43)	1665 (31.67)	11.9 (1.03)	71.9 (6.24)	83.8 (7.27)
Delay	23 (.44)	916 (17.43)	939 (17.87)	3.7 (.32)	38.6 (3.36)	42.3 (3.68)
Prohibit	0	0	0	0	0	0

deferred reprocessing decision; i.e., the lower return of benefits from the recycle of recovered products in the near-term, and the long-term implications on the electrical sector of a deferred LMFBR program. On the basis of economic considerations alone, the permit option would appear to be the optimal choice over delay or prohibit options.

Table 8.2

EXPECTED VALUE DOMESTIC SOCIAL COSTS
(In Billions of 1975 Dollars (mills/kWh))

Decision Options	HE&S		NT&S	
	0%	6%	0%	6%
Closed Cycle (Permit)	1.7 (.03)	.31 (.005)	.0016 (.00003)	.0002 (.000005)
Open Cycle (Prohibit)	1.7 (.03)	.31 (.0046)	.0033 (.00006)	.0004 (.00001)

Results of the examination of the domestic social cost categories inclusive of health, environmental, and safety (HE&S) effects in addition to nuclear theft and sabotage (NT&S) considerations indicate the dominance of HE&S over NT&S (Table 8.2). Moreover, it was concluded that differences between open- and closed-cycle HE&S social costs are virtually indistinguishable because of the trade-off between front- and back-end risks. Drawing upon representative nuclear theft and sabotage event sequences and assigning likelihood estimates on event occurrence, a quantitative

range was obtained for NT&S risks. It was found that the closed-cycle NT&S risks are greater than the NT&S risks of the open cycle by a factor of ~ 2 . However, these differences are so small as to be negligible when compared to the social costs related to HE&S risks.

Finally, domestic social costs are compared to total reprocessing economic benefits in billions of dollars and in mills/kWh (Table 8.3). A comparison of the differential domestic social costs with economic benefits reveals a factor of $\sim 5 \times 10^5$ between options. The permit option exhibits the largest positive margin between benefits-costs, indicating its preferability over delay or prohibit options.

Table 8.3

EXPECTED VALUE COMPARISON OF TOTAL ECONOMIC BENEFITS
WITH DOMESTIC SOCIAL COSTS
(1975-2050)

A. In billions of 1975 dollars

Decision Options Outcome Values	Permit		Delay		Prohibit	
	0%	6%	0%	6%	0%	6%
1. Benefits						
-- Direct	65	11.9	23	3.7	0	0
-- Indirect	1600	71.9	916	38.6	0	0
Total (v_e)	1665	83.8	939	42.3	0	0
2. Costs						
--HE&S	0 (1.7)	0 (.31)	0 (1.7)	0 (.31)	0 (1.7)	0 (.31)
--NT&S	.0017 (.0033)	.0002 (.0004)	.0006 (.0022)	.0001 (.0003)	0 (.0016)	0 (.0002)
Total (v_g)	.0017	.0002	.0006	.0001	0	0
3. $v_e - v_g$	1665	83.8	939	42.3	0	0

B. In mills/kWh for a capacity factor of 60% during a nominal year

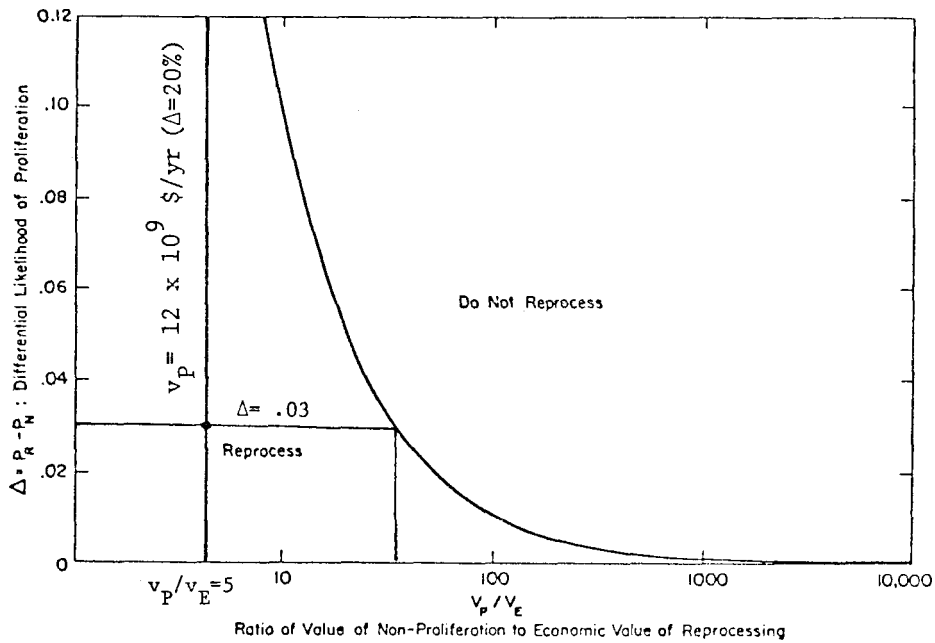
Decision Options Outcome Values	Permit		Delay		Prohibit	
	0%	6%	0%	6%	0%	6%
1. Benefits						
--Direct	1.24	1.03	.44	.32	0	0
--Indirect	30.43	6.24	17.43	3.36	0	0
Total (v_e)	31.67	7.27	17.87	3.68	0	0
2. Costs						
--HE&S	0 (.03)	0	0 (.03)	0	0 (.03)	0
--NT&S	.00003 (.00006)	.000025	.000015 (.000045)	.000011	0 (.00003)	0
Total (v_g)	.00003	.000025	.000015	.000011	0	0
3. $v_e - v_g$	31.67	7.27	17.87	3.68	0	0

* Discounted to year 1975 @ 0% and 6%. Values in parentheses denote actual social costs used to determine differential social cost values shown.

B. Policy Implications of Nuclear Proliferation Risk

The major trade-off between reprocessing economic benefits and social costs arises when considering nuclear proliferation risk. Because the actual outcomes of nuclear proliferation are debated, it is not clear that proliferation constitutes a real social risk. However, this study has adopted the perspective that proliferation does result in adverse effects, and has gone on to analyze proliferation as an additional risk U. S. society must face, regardless of reprocessing decision option chosen. The question examined was the implication of U. S. reprocessing decision options on nuclear proliferation rates. On the basis of arguments made in Chapter 7, it was shown that reprocessing policy hinges on the value U. S. society places on non-proliferation (v_p), and on the differential likelihood of proliferation between reprocessing decision options (Δ). A policy region diagram was derived indicating how the decision depends on the assigned value of v_p and the assessed value for Δ (Figure 8.1). It was pointed out that a reasonable range for v_p might be 1-100 billion dollars per year, as reflected by today's U. S. defense expenditures, and considerations related to the finiteness of the nation's wealth, i.e., ability to pay for increased safety.

Figure 8.1 Expanded Scale Policy-Region Diagram



On the basis of the 12 billion dollar per year estimate for v_p , derived by examining U. S. response to previous proliferation events, it was shown that Δ must be at least 20% before the delay option would be preferable over that of permit. When compared to the 3% upper bound estimate for Δ derived by comparing the commercial power plant-commercial reprocessor route to weapons material with some eight others currently available, a factor of at least 7 between reprocessing social benefits-costs is indicated (Fig. 8.1). Thus, it appears that the permit option is preferable over those of delay or prohibit, and that a deferral policy toward reprocessing is not logically justifiable on the basis of proliferation arguments alone.

Other arguments used to support the deferral policy, such as that the U. S. should defer reprocessing to provide an "example" for others to follow, may also prove faulty. The reprocessing decision faced by other countries may be more a matter of strict energy economics than is the case in the U. S. Countries such as France and Japan have no extensive coal reserves on which to depend, and are less willing to pay for swing fuels such as oil and natural gas. Thus, reprocessing-breeder benefits may prove relatively larger in these countries than in the U. S. Moreover, such societies may place different values on non-proliferation; the fact that their GNPs are smaller than that of the U. S. implies that they are less able to afford large expenditures to reduce proliferation risk. For less developed countries (LDCs), the benefits-costs of reprocessing may also be viewed quite differently. It may be that nuclear power decisions in LDCs reflect less the influence of technological risks and more the economic implications than for wealthy countries that can afford to ensure that risks remain at suitably low levels. Thus, just as different individuals express different risk preferences, different societies may also adopt different policies toward risk acceptance. These differences of perception should not be ignored by policy-makers bent on influencing decisions made in other countries, for what is perceived by one society as a large, adverse risk cannot be guaranteed to be viewed in the same way by others.

C. General Conclusions

The purpose of this study has been to analyze the economic and social implications of the U. S. reprocessing decision. By applying the methods of formal decision analysis, it has been shown that conclusions can be drawn on a quantitative, logical basis even in the face of large uncertainties. Because many of the factors affecting the social costs have been assigned representative values, the study conclusions cannot be construed as the final word on the reprocessing question. Rather, this study serves as an example of how social decisions may be analyzed in a quantitative fashion, providing useful input to the decision-making process.

At a time when legislators are faced with decisions of an ever more technological nature, some of which invoke heated controversy (e.g., licensing of the SST, the saccharin controversy, use of pesticides, air pollution, and coal strip-mining issues, etc.), studies which act to clarify matters in an objective fashion can be extremely useful. This is not to suggest that analysis should (or can) replace the legislative decision-making process, although some have opposed analysis for such reasons (see Lovins [108] and Hoos [109]). Rather, what is proposed here is that legislators make use of the *analytic* process in addition to the *adversary* process to heighten their own (and the public's) awareness of the issues. In this way, decisions may be based upon reasoned conclusions rather than on sheer rhetoric (see Howard [110] and Mishan [58]).

Chapter 9

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Appendix A

CONDENSED HISTORY OF CIVILIAN NUCLEAR INDUSTRY, DOMESTIC SAFEGUARDS AND ARMS CONTROL

In the United States, the history of civilian nuclear power began in 1946 with the formation of the Atomic Energy Act authorizing the government's key supervisory role in nuclear power's commercial development. This early act underlies current administration positions on the strict control of nuclear materials, then of interest because of the arms race with the U.S.S.R., and now of concern because of the rise of worldwide terrorism and the fear of nuclear proliferation.

In 1954, a major revision of the Atomic Energy Act occurred with President Eisenhower's change in policy toward commercial nuclear power expressed in his famous "Atoms for Peace" speech delivered at the United Nations. This policy helped stimulate the world's desire for nuclear research and commercial reactors, which were sold at highly subsidized prices. Congress loosened controls over nuclear materials to promote the private nuclear sector, and the International Atomic Energy Agency (IAEA) was organized to safeguard and assist the growing worldwide nuclear industry. During the 1960's, this policy was generally continued.

Then, in the 1970's, a resurgence of interest took place in the subject of safeguards and nuclear proliferation in reaction to several key events: (i) the increase in terrorist acts, with airplane hijackings and urban guerrilla warfare becoming more commonplace, (ii) the findings of several investigations that existing safeguards were "inadequate", (iii) the detonation of a nuclear explosive by India in 1973 demonstrating its newly developed nuclear weapons capability, and (iv) public concern about the viability of nuclear power as an acceptable energy source. In response to these events, the government reorganized several agencies charged with responsibility in these matters and amended and passed stringent regulations on the export of sensitive technologies and the handling and transportation of nuclear materials. With regard to domestic reprocessing, the decision on commercialization was deferred until the results from studies of "proliferation-resistant" systems become available (presumably by 1980).

Table A.1 Significant History of Civilian Nuclear Industry, Domestic Safeguards, and Arms Control

<u>Year</u>	<u>Action</u>
1946	<u>Atomic Energy Act (Acheson-Lilienthal)</u> : Authorized the government to supervise the civilian nuclear energy program. Nuclear materials were kept under tight security because of arms race with U.S.S.R.
1954	<u>Revision of Atomic Energy Act-- "Atoms for Peace"</u> : Congress loosened controls over nuclear materials to promote private nuclear industry; Eisenhower introduced "Atoms for Peace" in United Nations speech.
1957	<u>International Atomic Energy Agency (IAEA) Formed</u> : The IAEA was set up to both assist and safeguard the worldwide nuclear industry. It requires data from member NPT and non-NPT states on inventories of nuclear materials, sends inspectors to review practices, and generally surveys commercial nuclear industry to be sure no illegalities occur.
1966	<u>AEC Establishes ad hoc Advisory Panel on Safeguarding SNM (R. Lamb, Chairman)</u> : Panel's report stated: "There is no evidence that SNM used in domestic programs have been diverted to unauthorized use in this country or abroad. But what has been good enough in the past may not meet the test of the future." The report added that "safeguards.. have not always received adequate attention" and recommended strengthening physical protection standards and the establishment of a single AEC office to deal with the safeguards program.
1968	<u>Nuclear Proliferation Treaty (NPT)</u> : Consists of a "deal" between nations with weapons and those without. Non-nuclear weapons states who sign and ratify the agreement give up the right to manufacture nuclear weapons, while weapons states agree to provide the world with nuclear technology for peaceful uses, and work toward disarmament.
1972	<u>President Nixon Establishes Cabinet Committee to Combat Terrorism</u> : Cabinet committee established because of the increasing rate of terrorist activity around the world.
1973	<u>AEC Amends Part 73, Title 10 of Code of Federal Regulations</u> : AEC publishes revised regulations for physical protection of fixed sites and special nuclear materials in response to GAO.

<u>Year</u>	<u>Action</u>
1973 (Nov)	<u>GAO Issues Safeguards Report</u> : Concludes: "Our review of the security system of two of the three licensee/contractors showed conditions which significantly limit their ability to prevent, detect, or effectively respond to a possible SNM diversion or attempt to divert." The GAO recommended that the AEC strengthen its in plant physical protection of SNM.
1974 (Apr)	<u>Willrich and Taylor Study Released [4]</u> : Energy Policy Project of the Ford Foundation releases <u>Nuclear Theft: Risks and Safeguards</u> . This study is one of the first attempts to examine the overall safeguards problem on a domestic or international level. Conclude that U.S. system of safeguards incomplete, and that AEC should consider forming a Federal Security Service to design safeguards for each type of nuclear facility. They also called for the government to discuss the safeguards problem with other countries to begin to solve international problems.
1974 (Apr)	<u>GAO Releases Second Report on Safeguards System</u> : Concerned with transportation, GAO found nuclear shipments were inadequately protected to prevent or detect a diversion attempt. They suggested the AEC look into the possibility of having the government operate a transportation system for SNM.
1974 (Apr)	<u>Rosenbaum Report Placed in Congressional Record by Senator Ribicoff</u> : This report was commissioned by the AEC to investigate nuclear safeguards issues. It concluded that significant changes were needed in the safeguards system because of the increase in terrorist group activities. Recommended that the AEC adopt a safeguards review procedure like that for examining the safety of nuclear power plant design, and called for the establishment of a Federal Security Force.
1974 (Aug)	<u>WASH-1327 Released</u> : This preliminary GESMO report found that the safeguards objective of achieving a significant level of protection against sabotage or terrorist acts would not be met by current safeguard measures. It urged implementation of collocation of reprocessing and MOx fabrication plants, new fixed site barrier requirements, upgrading of guard functions, improved accounting methods, the use of spiked plutonium, and enhanced transportation security.
1974	<u>Energy Re-Organization Act Passed by Senate</u> : Abolished AEC and created ERDA and NRC.

<u>Year</u>	<u>Action</u>
1975 (Jan)	<u>CEQ Issues Letter: President's Council on Environmental Quality (CEQ)</u> recommend that a safeguards program cost-benefit analysis precede any final NRC action on the plutonium recycle question.
1975	<u>NPT Review Committee:</u> Conference held on effects of NPT; record feelings that weapons states not living up to their part of the "deal".
1977 (Mar)	<u>Ford-MITRE Report Issued, Nuclear Issues and Choices:</u> In discussing nuclear terrorism, study notes that "nuclear weapons can easily be manufactured by capable terrorists" but that "reprocessing fuel elements would be beyond their capabilities" (p.314, [6]). They point out that "current physical security arrangements for both nuclear facilities and materials require strengthening..[but need not] endanger civil liberties." They also note that "If plutonium is not recycled, the opportunities for plutonium theft in civilian industry are essentially eliminated" because "theft of spent fuel is unlikely since it is extremely radioactive and can be handled only with special shielding and equipment".
1977 (Apr)	<u>President Carter Announces a Nuclear Non-Proliferation Policy Calling for Indefinite Deferral of Reprocessing:</u> Policy encourages the commencement of domestic and international studies of alternative fuel-cycles.
1977	<u>London Suppliers Conference:</u> Secret meeting of nations that export nuclear equipment. Carter hopes to get industrial nations to refrain from exporting "sensitive" technologies that can be used to facilitate a nation's desire to develop weapons capability.
1977 (Jul)	<u>APS Study, Section on Safeguards:</u> In absence of GESMO supplement on safeguards, the American Physical Society (APS) looked at technical safeguard barriers and made recommendations on implementation: "it appears quite possible that effective security can be imposed throughout the fuel cycle".
1978 (Jan)	<u>NRC terminates GESMO Hearings:</u> NRC will re-examine the reprocessing decision after the completion of ongoing alternative fuel cycle studies. Plans to issue GESMO safeguards supplement as a staff technical report.

Appendix B

SUPPORT CALCULATIONS FOR CHAPTER 4

B.1 Support Calculations for Deterministic Phase

Following the decision analysis cycle described in Chapter 1, a systems approach has been utilized to model the LWR nuclear fuel cycle and calculate fuel cycle expansion costs (Fig. B.1). In the deterministic phase, a fuel cycle simulation model is used to calculate economic outcome values for various reprocessing expansion paths. The calculation is performed by following a series of steps making up the calculational procedure of the fuel cycle simulation model.

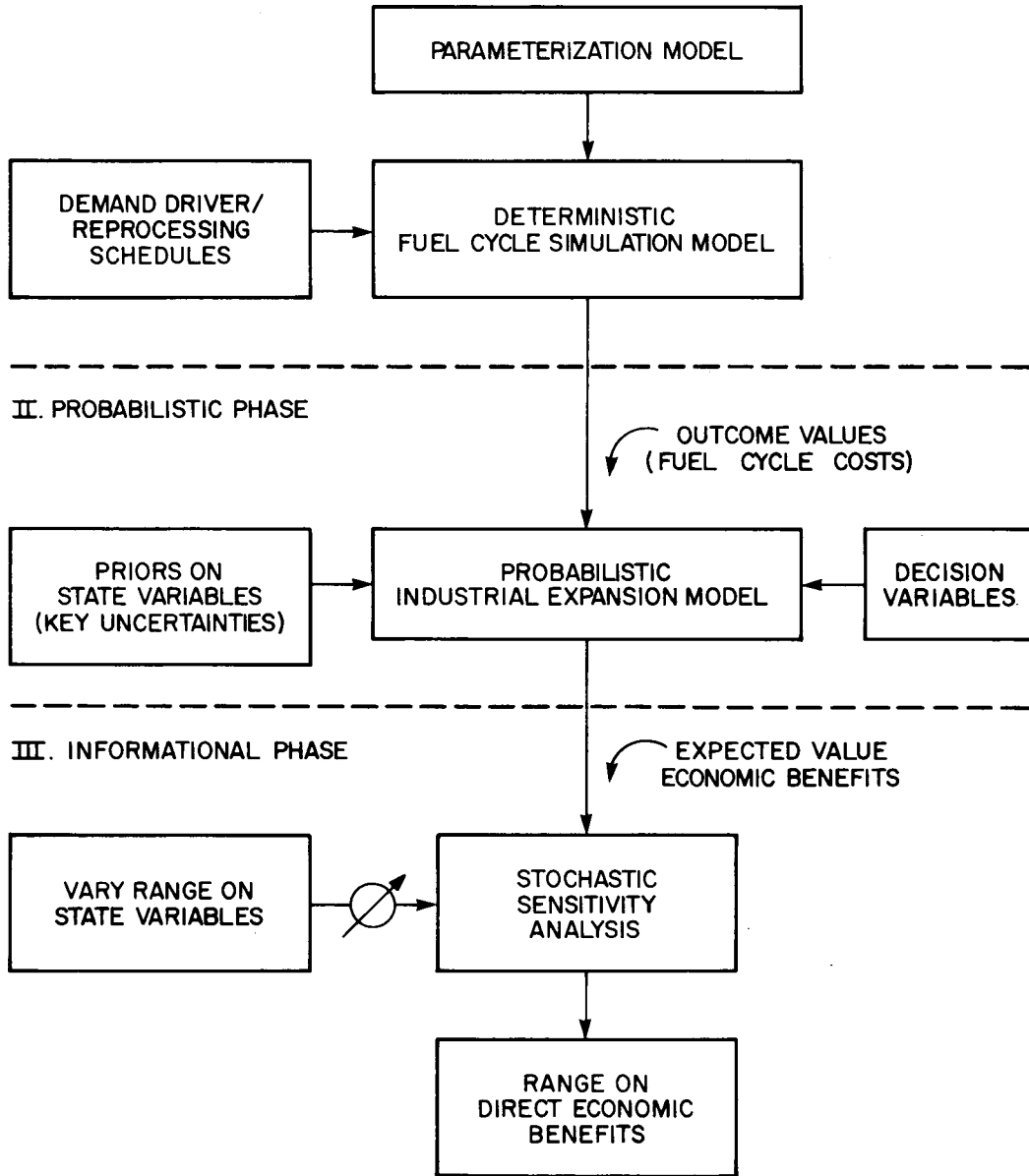
FUEL CYCLE SIMULATION MODEL: CALCULATIONAL PROCEDURE

#	Step	Description
1.	Calculate metallic uranium flow to reactors (MTU) (see Chapter 4, Table 4.2).	For each nuclear supply scenario defined (see Appendix B, Sections B.2.2-3), the total energy out (TkwH) and Fission Thermal Energy (10^9 MWdt) are determined. Then the Fission Thermal Energy is divided by assumed values for the Burn-Up (β) to determine metallic uranium flow to reactors.
2.	Calculate milled uranium flow to enrichment plant (ST - U_3O_8)	The input to the fabricator is the output, or product stream, of the enrichment plant. Assuming a tails assay of .2% and product enrichment of 3%, reflecting current practice [64], the feed-to-product ratio is determined (.1825). This factor is divided into the values for the fabricator input flow to determine the enrichment feed flow in MT. The feed flow is equal to the output of the uranium mill. To convert MTU to ST - U_3O_8 , the feed flow in MTU is multiplied by a factor of

$$1.298 = \frac{3(238) + 8(16)}{3(238)} \frac{U_3O_8}{U} \times 1.1 \frac{ST}{MT}$$

Figure B.1 Systems Model of the LWR Nuclear Industry

I. DETERMINISTIC PHASE



3. Calculate reprocessing strategy-nuclear supply dependent quantities of reprocessed fuel, recovered uranium, recycled plutonium, MOX and UO₂ fuel fabricated (Table B.2); reprocessing, MOX fabrication and HLW disposal requirements (Table B.3). Reprocessing strategies are defined as a function of nine industrial expansion paths (see Fig. 4.1); for each expansion path, the spent fuel processed in the indicated time period is calculated as a function of the reprocessors assumed operating at full capacity (see Table 4.3). By 2050 all spent fuel produced is assumed to be reprocessed. Thus, the difference between paths 1-3 depends upon the introduction date and growth rate of reprocessing facilities, while paths 4-8 differ as to how long reprocessing takes place before being discontinued completely.
4. Calculate milled uranium, enrichment feed, and separative work savings. From the recovered uranium and MOX fuel fabricated above, the amounts of milled uranium, enrichment feed and separative work savings can be calculated. The calculations are done excluding U-236 or U-234 penalties, since DOE policy at present is not to subtract U-236 or other penalties in making reprocessing calculations (details concerning U-236, etc., penalties are found in Refs. [111,112]).
5. Calculate outcome values for 9 expansion paths as a function of economic state of the world for years 1975-2005; 2006-2050. From the logistics information calculated, outcome values as a function of economic state-of-the-world are calculated in a deterministic mode; i.e., no probabilities are assigned at this step to the economic state-of-the-world. The fuel cycle unit cost assumptions used are shown in Table B.1.

Table B.1

FUEL CYCLE UNIT COST ASSUMPTIONS
(1975 \$)

Process	Range		Units
	Lo	Hi	
Mined/Milled Uranium	30	100	\$/lb U ₃ O ₈
Enrichment	75	125	\$/kgSWU
Fabrication (MOX)	150	300	\$/kgHM
Reprocessing	150	350(500)	\$/kgHM
Waste Disposal	50	90	\$/kgHM
Spent Fuel Disposal	100	200	\$/kgHM
Fabrication (UO ₂)	100		\$/kgU

Table B.2

STRATEGY-SUPPLY DEPENDENT QUANTITIES OF REPROCESSED FUEL, RECOVERED URANIUM, RECYCLED PLUTONIUM, MOX AND UO₂ FABRICATED FUEL

Strategy and Nuclear Supply Case	Spent Fuel Processed ^{a/} (10 ³ MTHM)		Recovered Uranium ^{b/} (10 ³ MTU)		Recycled Plutonium ^{b/} (10 ³ MT-PuO ₂)		MOX Fuel Fabricated ^{c/} (10 ³ MTHM)		UO ₂ Fuel Fabricated ^{d/} (10 ³ MTU)	
	1975-2005	2006-2050	1975-2005	2006-2050	1975-2005	2006-2050	1975-2005	2006-2050	1975-2005	2006-2050
	1 A	59.5	80.3	56.4	75.5	1.2	1.6	24	32	41.5	55.0
G	235.3	385.9	221.4	362.7	4.7	7.7	94	154	165.0	264.3
2 A	36.0	103.8	33.8	97.6	.7	2.1	14	42	48.7	70.6
G	79.5	541.7	74.7	509.2	1.59	10.8	32	216	211.4	371.2
3 A	28.5	111.3	26.8	104.6	.57	2.2	11	44	51.0	76.6
G	74.0	547.2	69.6	514.4	1.48	10.9	30	218	213.1	375.1
4	30.0	0	28.2	0	.6	0	12	0	(-9020)	0
5	15.0	0	14.1	0	.3	0	6	0	(-4500)	0
6	22.5	0	21.2	0	.45	0	9	0	(-6750)	0
7	7.5	0	7.1	0	.15	0	3	0	(-2250)	0
8	12.0	0	11.3	0	.24	0	5	0	(-3600)	0

^{a/} All spent fuel produced before 2050 is assumed reprocessed before 2050.

^{b/} Assumes 94% of combined UO₂ and MOX fuel is recovered uranium, 2% recyclable plutonium, and 4% high-level waste. Represents an aggregated UO₂-MOX futuristic scenario -- 6% Pu_g in UO₂ once-through, 5% in MOX fuel.

^{c/} Assumes Pu ~ 5% of MOX fuel by weight. The mode of recycle is natural and enriched uranium mixed with fissile plutonium. Thus, ~ 20 x MT PuO₂ recovered = MTHM (MOX fuel).

^{d/} MTUO₂ needed = total MTUO₂ fuel without recycle - (30/38) x (MTHM MOX fuel), since ~ 38 MTHM MOX fuel required to produce same amount of electrical energy from ~ 30 MTUO₂ fuel

Table B.3

REPROCESSING, MOX FABRICATION AND HLW REQUIREMENTS

Reprocessing Expansion Path	Reprocessing Requirements (10 ³ MTU)				MOX Fabrication Requirements (10 ³ MTHM)				High-Level Waste Disposal Requirements (10 ³ MTHM)			
	A		C		A		C		A		C	
	1975-2005	2006-2050	1975-2005	2006-2050	1975-2005	2006-2050	1975-2005	2006-2050	1975-2005	2006-2050	1975-2005	2006-2050
1	59.5	80.3	235.3	385.9	24	32	94	154	2.4	3.2	9.4	15.4
2	36	103.8	79.5	541.7	14	42	32	216	1.4	4.2	1.7	21.7
3	28.5	111.3	74	547.2	11	44	30	218	1.1	4.5	1.4	21.9
4	30	0	30	0	12	0	12	0	1.2	0	1.2	0
5	15	0	15	0	6	0	6	0	.6	0	.6	0
6	22.5	0	22.5	0	9	0	9	0	.9	0	.9	0
7	7.5	0	7.5	0	3	0	3	0	.3	0	.3	0
8	12.0	0	12.0	0	5	0	5	0	.5	0	.5	0

B.2 Support Calculations for Probabilistic Phase

The outcome values associated with each economic state-of-the-world are used in the probabilistic phase where expected value fuel cycle expansion costs are estimated.

PROBABILISTIC PHASE: CALCULATIONAL PROCEDURE

#	Step	Description
6.	Calculate state-of-the world likelihoods for mutually held cost states	After priors are assigned to key parameters (see Section B.3), state-of-the-world likelihoods are calculated for the 32 possible states held in common between expansion paths 1-8. This is accomplished by taking the probability associated with each key parameter making up the particular state, and multiplying them together. This is done as a function of the nuclear supply state.
7.	Calculate preliminary expected values for reprocessing expansion paths	The preliminary expected values for reprocessing expansion paths are calculated by multiplying the economic outcome values and the likelihoods associated with each economic state-of-the-world together for the years 1975-2005 and 2006-2050.
8.	Calculate final expected values for reprocessing expansion paths (Table B.4)	The preliminary expected values for each path are multiplied by the priors on the expansion paths to obtain final expected values for each path. Then the appropriate paths are summed to determine the expected value costs for permit, delay and prohibit decision options.
9.	Discount expected value costs	Discounting is accomplished by applying discount factors to cost incurred in each of ten defined time periods, determined as a function of nuclear supply scenario.
10.	Calculate total fuel cycle cost expected values and direct benefits	From the total fuel cycle expected value costs, direct benefits are obtained by subtracting the permit and delay costs from the prohibit costs (see Fig. 4.4).

Table B.4

FINAL EXPECTED VALUES FOR REPROCESSING EXPANSION PATHS

Expansion Path	Priors on Expansion Paths	Preliminary Expected Values (1975-2005)	Expansion Path Expected Values (1975-2005)	Preliminary Expected Values (2006-2050)	Expansion Path Expected Values (2006-2050)	
PERMIT	1	.8	120.8	96.6	179.6	143.7
	2	.12	132.8	15.9	191.7	23.0
	4	.0225	138.0	3.1	204.4	4.6
	5	.0075	141.4	1.1 Total:	211.2	1.6 Total:
	9	.05	146.6	7.3 124.0	212.6	10.6 183.5
DELAY	3	.48	135.0	64.8	197.1	94.6
	6	.09	138.9	12.5	204.4	18.4
	7	.03	143.3	4.3	208.3	6.3
	8	.18	142.2	25.6 Total:	207.2	37.3 Total:
	9	.22	146.6	32.3 139.5	212.6	46.8 203.4
PROHIBIT	9	1	146.6	146.6	212.6	212.6

B-6

B.3 Basis for Prior Assignments

B.3.1 Priors on Pre-2005 LWR Nuclear Supply Scenarios

The history of U. S. nuclear supply forecasting has been characterized by uncertainty and major fluctuations. In fact, because of problems of both a political and technical nature, forecasts have been slipping. However, because of the long lead times (10-15 years) involved in constructing power plants, near-term nuclear supply is relatively certain and can be made the starting point for forecasting the more long-term future of LWR nuclear supply. This approach has been taken in this study, beginning with the 1978-1987 commercialization schedule provided in Ref. [113]. (The resulting projections for the years 1975-2005 are shown in Fig. B.5.)

Priors on nuclear supply are conditional upon total electricity demand, and are shown in Fig. B.2. A discrete approximation of these curves is made rendering the values given in Chapter 4, Table 4.9.

Figure B.2 Priors on LWR Nuclear Supply Conditioned On Total Electricity Demand (Year 2000)

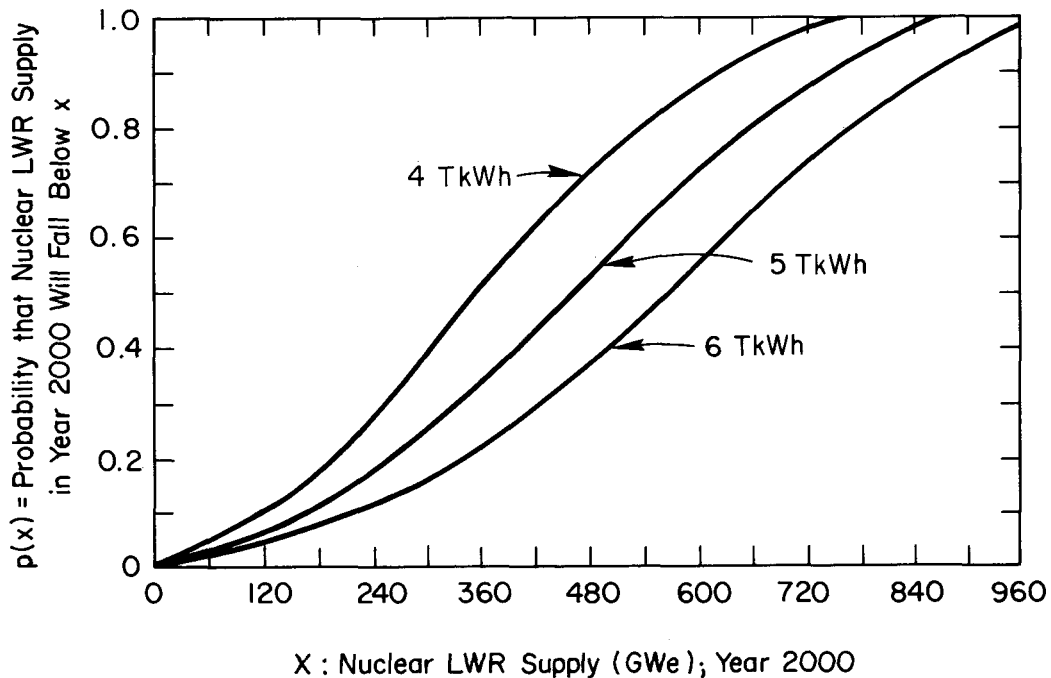
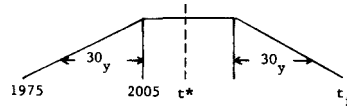


Table B.5

POST-2005 EXPECTED VALUE NUCLEAR SUPPLY

Pre-2005 Supply Scenario	Total Cumulative GW(e) 1975-2005	G ₁		G ₂		G ₃		EV(G) 2005-2050
		t _f = 2035	P* t _f = 2045	G† t _f = 2055	P t _f = 2055	G t _f = 2065		
A	2770	2770	2070	4223	5370	5412	3760	
B	4386	4386	7446	7564	10506	10702	6649	
C	5975	5975	10175	10315	14375	14640	9075	
D	7045	7045	12445	12635	15445	18230	10955	
E	8305	8305	14905	15115	21505	22010	13176	
F	9720	9720	18120	18460	26520	27180	15941	
G	10930	10930	20430	20820	29930	30700	17968	

* P = "Plateau" Post-2005 LWR Supply Scenario:



† G = "Growth" Post-2005 LWR Supply Scenario:

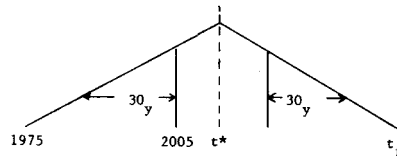
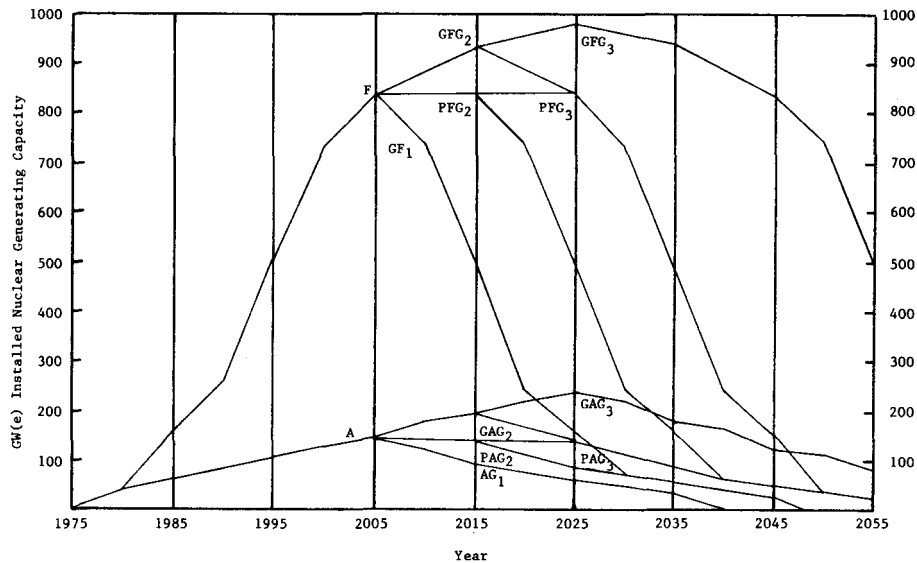


Figure B.3 Representative Range on LWR Supply (1975-2050)



B.3.2 Post-2005 Nuclear Supply Scenarios: Priors on AET Introduction Date and Growth Rate

After the turn of the century, nuclear supply forecasts are further complicated by the effect of AET introduction date and subsequent growth rate. To provide a range on possible LWR post-2000 futures, the effects of AET introduction dates are examined, assuming growth such that LWR phase-out is gradual, reflecting the 30-year normal lifetime of nuclear facilities. The phase-out is such that a symmetry centered about the date of AET introduction is evident (Table B.5). Until the AET is introduced, however, pre-2000 supply scenarios are assumed to branch out into two possible futures^{*}: (i) the case where the 2000 supply reached is not exceeded and acts as an upper bound; replacement of plants occurs so that a particular supply is maintained until the date of AET introduction ("plateau" future), and (ii) the case where LWR supply doubles every 30 years until the AET is introduced (domestic LWR "growth" future.)

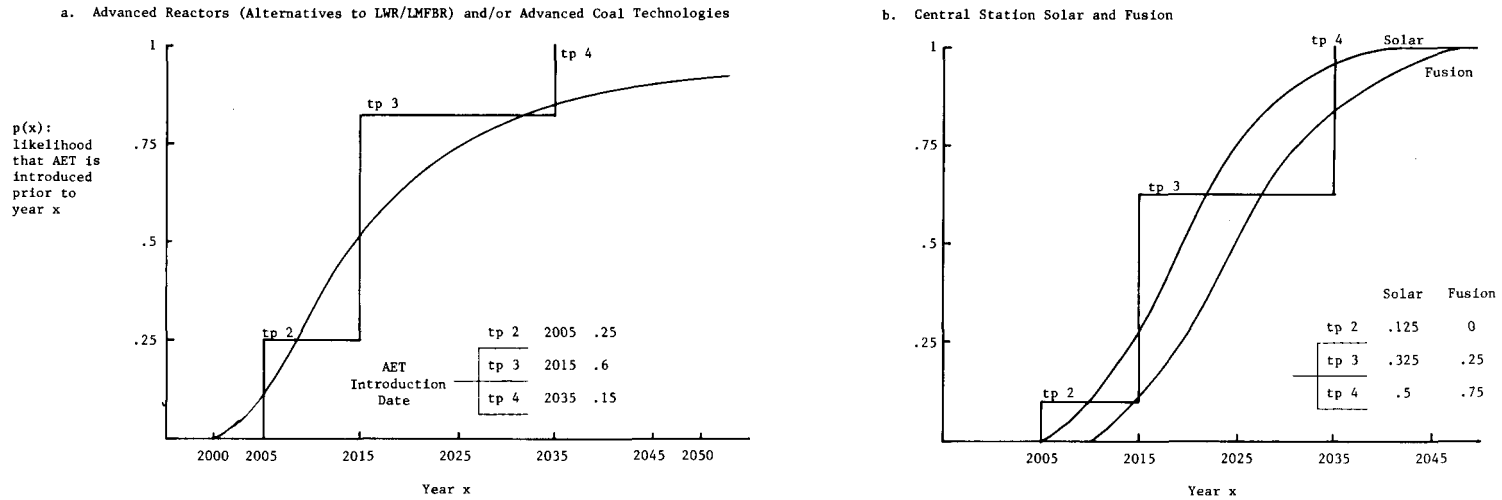
The prior distribution assigned to the AET introduction date suggests a three-way discrete lottery approximating the curve with dates 2005, 2015, and 2025 examined (Figures B.4-5). The distribution plotted is based on assumptions that the AET will not be introduced later than 2045 nor earlier than year 2000, and that the likelihood that it will be introduced prior to 2015 is equal to the likelihood that it will be introduced after the year 2015. (This assumption also holds for AETs such as alternative reactor schemes designed specifically to replace LWRs.)

B.3.3 Basis for Prior Assignments on Reprocessing Unit Cost

A range on reprocessing unit cost of between 150-450 \$/kg-HM (1975 dollar terms) can be established from recent U. S. studies on reprocessing economics [47]. A major component of the discrepancy between estimates can be accounted for by the uncertainty surrounding future ownership of reprocessing services, as reflected in Europe where prices range between

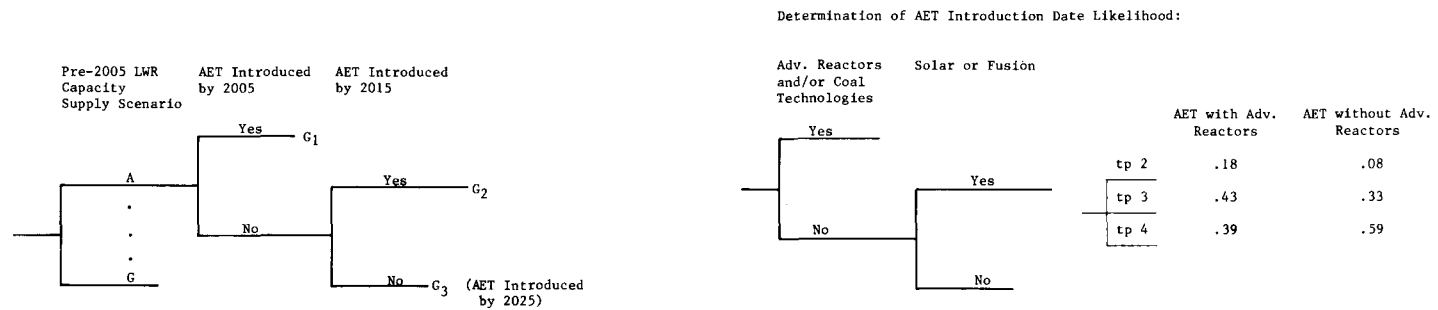
* It is assumed that, upon depletion of uranium reserves at 35 \$/lb U₃O₈, more costly ore is utilized as necessary until commercial introduction of the AET.

Figure B.4 Prior Distributions on AET Introduction Date



B-10

Figure B.5 Determination of Post-2005 Nuclear Supply Scenarios (LWR)



400-1000 \$/kg-HM (as of 1978): a result of the small scale at which the plants are now operating and the plant-financing structure [114].

The Edison Electric Institute (EEI) notes that the dominant component of reprocessing unit cost is due to recovery of capital investment. The annual charge for capital recovery is highly dependent on the ownership structure, in particular the debt-equity ratio and the return of equity criteria employed in the implementation of the venture [115]. Thus, even though engineering studies of capital cost may disagree very little (for a 1500 MT/year reprocessor, estimates of between 500 to 600 million dollars are not uncommon, exclusive of interest during construction and in 1975 dollar terms), service cost estimates can vary widely, depending on what assumptions are made concerning debt financing (Fig. B.6).

The high cost band in the figure is characteristic of a low debt, high rate-of-return financing consistent with the major capital undertakings of large corporations. The low band of estimates is characteristic of a more leveraged financing, recognizing that such an arrangement is keyed to the assumption that commercial risks are distributed between the special organization and utility customer. This lower band reflects special project organizations that might pattern themselves after the "Connecticut Yankee" structure (45% debt corporation owned by utilities) or a United Enrichment Associates (UEA) consortium (a now defunct 85% debt organization).

It is of interest to note that the West Germans have recognized the relationship between ownership and service cost. Twelve leading FRG utilities have established the German Reprocessing Company (DWK), which will operate the first German fuel cycle center. As of 1978, the DWK has submitted a proposal to the German government for approval, expected to take three years. Pending approval, construction will begin in 1981 so that reprocessing may begin by 1986 [116].

Whether or not American utilities will decide to follow the German example is uncertain. Allied Gulf Nuclear Services (AGNS) has completed a series of talks with major U. S. utilities, and it appears that utilities may act favorably to such a plan [114]. Another motivation for utility involvement is provided by the U. S. government's reluctance to provide civilian reprocessing services, as reflected in the Carter

Figure B.6 Cost of Service vs. Percent Debt

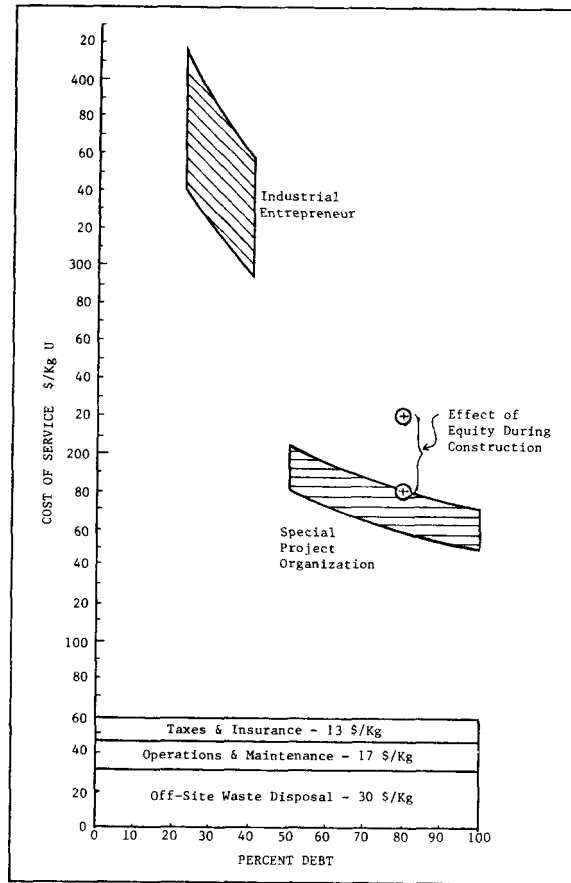


Table B.6

STEP-WISE APPROXIMATIONS ON PRIORS FOR REPROCESSING UNIT COST
AS A FUNCTION OF TIME PERIOD (\$/kg-HM, 1975 \$)

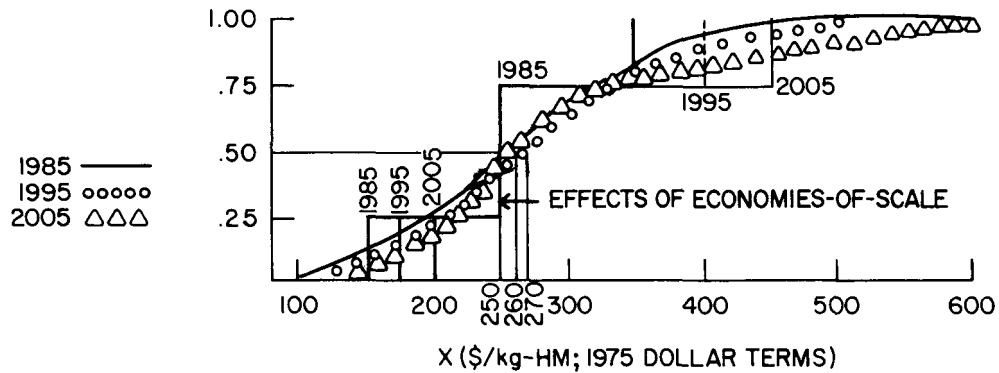
Time Period	High (.25)	Medium [*] (.50)	Low (.25)	Expected Value
1985	350	250	150	250
1995	400	250	175	270
2005 and beyond	450	250	200	290

^{*}The effect of economies-of-scale is to decrease the unit cost as larger units become operable, thus tending to keep the distribution centered at a value of 250 \$/kg-HM. However, the tail of the distribution expands, reflecting the greater uncertainty as time increases.

Administration's recently formulated energy policy. Moreover, major industrial corporations do not appear overly enthusiastic to enter the reprocessing business, partly because of major past failures and financial losses (e.g., Nuclear Fuel Services West Valley plant, and General Electric's Morris, Illinois, plant).

Taking these considerations into account, prior distributions have been derived as a function of time period (Fig. B.7).

Figure B.7 Priors on Reprocessing Unit Cost and Step-Wise Approximations



Note that the effect of economies-of-scale for future facilities tends to move the distribution slightly to the left, counter-balancing trends that might tend to increase costs as time goes on. A step-wise approximation has been taken to establish cost estimates and their likelihood of occurrence (Table B.6). These "three-way lotteries" have been used in Chapter 4 to calculate economic cost-benefits. The general effect of time is to broaden the distribution, especially at the higher cost tail-end.

Appendix C

SUPPORT CALCULATIONS FOR CHAPTER 5

C.1 Description of the Fuel Substitution Model

The fuel substitution model calculates, for each time period t , the costs of producing electricity using the expected value mills/kWh unit cost for LWR-produced nuclear energy as the reference value. That is, the model calculates the dollar costs to *substitute* for LWR capacity as a function of time. The calculations are accomplished by following the procedure described below. Selected output from the computerized version of the model is also provided to further illustrate the procedure.

FUEL SUBSTITUTION MODEL: CALCULATIONAL PROCEDURE

#	Step	Description
Deterministic Phase:		
1.	Calculate total cumulative electricity demand (in TkWh) by time period (Matrix A: Dimension 3 x 4).	For the following time periods: (1) 1975-1995, (2) 1996-2015, (3) 2016-2035, and (4) 2036-2050, the cumulative electricity demand is determined based on the three scenarios (Low, Medium, and High) that were described in Chapter 4 (for year 2000, Low: 4 TkWh; Med.: 5 TkWh; and High: 6 TkWh). The implied demand curves are integrated over the specified time periods to arrive at cumulative figures.
2.	Calculate the nuclear LWR capacity supply (in TkWh) by time period (Matrix B: Dimension 3 x 4).	For each of the four time periods, the cumulative electricity supplied by LWR capacity is determined as a function of three scenarios based on the seven supply trajectories (in GWe) described in Chapters 3-4 (i.e., A-G: very low - very high). A capacity factor of 60% is used to convert the GWe supply curves to TkWh which are then integrated over time to arrive at cumulative figures.
3.	Calculate the non-LWR supplied electricity demand (in TkWh) by time period (Matrix C: Dimension 9 x 4).	Each row of matrix B is subtracted from Matrix A to form the 9 x 4 Matrix C representing all possible states-of-the-world with respect to remaining electricity demand.

4. Calculate the electricity supplied by coal-fired capacity (in TkwH) by time period.

The matrix C is multiplied by factors representing the percentage of remaining demand that can be supplied by coal-fired capacity in a given time period. Three 9 x 4 matrices (CL, CM, and CH = C) are formed representing the TkwH demand supplied by coal-fired capacity as a function of time period.
5. Calculate the electricity (in TkwH) supplied by the LMFBR as a function of the date and rate of introduction of the LMFBR, coal-fired and LWR capacity supply, and total electricity demand for each time period.

The matrices C minus CL, CM, and CH, representing the remainder of demand not met by either coal-fired or LWR capacity, are multiplied by each row of the 4 x 4 matrix ROI, which specifies the rate-of-introduction of the LMFBR as a function of the time period of its introduction. Thus, 12 separate 9 x 4 matrices are formed describing all possible LMFBR electricity supply states-of-the-world.
6. Calculate the electricity (in TkwH) supplied by the AET as a function of LMFBR, coal-fired, and LWR capacity supply, and total electricity demand for each time period.

The matrices representing the remainder of demand not met by the LWR, coal-fired, or LMFBR capacity are multiplied by the 4 x 4 matrix ROI, which specifies the rate-of-introduction of the AET as a function of the time period of its introduction.
7. Calculate the electricity (in TkwH) supplied by the SWT, or left unsupplied, as a function of the SWTs availability with respect to time period.

Finally, the matrices representing the remainder of demand not met by any of the other technologies are calculated. These "left-over" matrices are assumed to either represent the electricity supplied by the SWT or the demand unsatisfied by the available capacity supply. The interpretation of these matrices depends on the priors assigned to the likelihood of SWT availability as a function of time (see Section C.2.2).

Probabilistic Phase:

1. Calculate the expected value coal cost-to-substitute (in mills/kWh) for LWR capacity.

The matrices CL, CM, and CH are multiplied by the priors on total electricity demand, nuclear capacity supply, and expected value coal cost-to-substitute for LWR capacity as a function of time period. These matrices are coalesced by multiplying by the priors on coal supply and adding to arrive at the matrix representing the expected value coal cost-to-substitute for LWRs.

As a Function of Reprocessing Decision Alternative:

2. Calculate the expected value LMFBR cost-to-substitute for LWRs. Since the priors on LMFBR date of introduction are conditional upon reprocessing decision alternative, the expected value costs of substitution for the LMFBR, AET, and SWT are calculated for each alternative separately. The expected value mills/kWh LMFBR cost-to-substitute for LWRs multiplies the 12 separate 9 x 4 matrices representing LMFBR supply states-of-the-world, which are then coalesced by multiplying each entry by the appropriate priors on LWR and coal-fired capacity supply, and total electricity demand.
3. Calculate the expected value AET cost-to-substitute for LWRs. The expected value mills/kWh AET cost-to-substitute for LWRs multiplies the matrices representing AET supply states-of-the-world, which are then coalesced by multiplying each entry by the appropriate priors on LWR, coal-fired, and LMFBR capacity supply, and total electricity demand.
4. Calculate the expected value SWT cost-to-substitute for LWRs, and the social cost of Supply Constrained Demand (SCD). The matrices representing the remainder of demand left unsatisfied by the other technologies are multiplied by the priors on SWT availability and the expected value mills/kWh SWT cost-to-substitute for LWRs, as a function of time period, to determine the SWT dollar cost to substitute for LWRs. These matrices are also multiplied by one minus the priors on SWT availability and the social cost, in mills/kWh, of SCD, to determine the dollar costs of supply constrained demand. Then, each entry is multiplied by the appropriate prior values on LWR, coal-fired, LMFBR, and AET capacity supply, and total electricity demand, to coalesce the matrix into one value per time period.
5. Calculate the total undiscounted dollar cost-to-substitute for LWRs as a function of reprocessing decision option. All of the coalesced matrices for the various supply alternatives are added together as a function of time period, to generate the total dollar cost-to-substitute matrix.
6. Calculate the discounted dollar cost-to-substitute for LWRs as a function of reprocessing decision option, and the differential benefits. The total undiscounted dollar cost-to-substitute for LWRs are discounted by selecting the midpoint year for each of the four time periods and applying social discount rates of between 3-12% to determine discounted figures. The discounted figures are then subtracted between the reprocessing decision options of permit, delay, and prohibit to arrive at the discounted indirect economic benefits of reprocessing LWR fuel.

FUEL SUBSTITUTION MODEL CALCULATIONAL RESULTS FROM FOLDING-BACK EVENT TREE: RE: FIGURE 5.1, CHAPTER 5 IN HEISING THESIS

TIME-PERIODS EXAMINED: 1. 1975-1995, 2. 1996-2015, 3. 2016-2035, AND 4. 2036-2050

INPUT DATA

MATRIX A: TOTAL CUMULATIVE U.S. ELECTRICITY DEMAND IN TKWH

	1	2	3	4
LOW	25.00000	58.00000	67.00000	103.00000
MED	49.00000	116.00000	134.00000	206.00000
HI	60.00000	150.00000	180.00000	275.00000

MATRIX ROI: LMFBR/AET RATE-OF-INTRODUCTION (EXPRESSED AS % PERIOD(COLUMNS) AND TIME-PERIOD OF INTRODUCTION (ROWS))

	1	2	3	4
TP1	0.1000000	0.5000000	0.8000000	1.0000000
TP2	0	0.1000000	0.5000000	0.8000000
TP3	0	0	0.1000000	0.5000000
TP4	0	0	0	0.1000000

MATRIX B: CUMULATIVE LWR CAPACITY SUPPLY IN TKWH AS FUNCTION

	1	2	3	4
LOW	8.000000	25.00000	30.00000	25.00000
MED	11.60000	51.50000	59.30000	54.20000
HI	15.00000	65.00000	70.00000	65.00000

THE TOTAL COST-TO-SUBSTITUTE FOR LWRS FOR PERMIT IS:

TP1	TP2	TP3	TP4	
80.91412	94.34569	121.7054	TP4	605.0173

THE TOTAL COST-TO-SUBSTITUTE FOR LWRS FOR DELAY IS:

TP1	TP2	TP3	TP4	
82.66565	106.2565	163.0235	TP4	1234.157

THE TOTAL COST-TO-SUBSTITUTE FOR LWRS FOR PROHIBIT IS:

TP1	TP2	TP3	TP4	
82.66565	107.8396	183.9137	TP4	2127.151

MATRIX L: COAL COST-TO-SUB FOR LWRS IN MILLS/KWH

LOW	-3.400000	MED	0	HI	3.000000
-----	-----------	-----	---	----	----------

MATRIX N: PROBABILITY ESTIMATES(BASED ON PRIOR DISTRIBUTIONS)

	A-C	D	E-G
LOW	0.5400000	0.2400000	0.2200000
MED	0.3200000	0.3800000	0.3000000
HI	0.2100000	0.5100000	0.2800000

THE UNDISCOUNTED EV DIFFERENCES BETWEEN DECISION OPTIONS:

DIFFERENCES BETWEEN PERMIT VS DELAY

TP1	TP2	TP3	TP4		
1.751526	11.91080	TP3	41.31810	TP4	629.1394

DIFFERENCES BETWEEN PERMIT AND PROHIBIT

TP1	TP2	TP3	TP4		
1.751526	13.49394	TP3	62.20833	TP4	1522.134

DIFFERENCE BETWEEN DELAY AND PROHIBIT

TP1	TP2	TP3	TP4		
0	1.583145	TP3	20.89023	TP4	892.9946

VECTOR Y: LIKELIHOODS ON TOTAL ELECTRICITY DEMAND

LOW:	0.6000000	MEDIUM:	0.3000000	HIGH:	0.1000000
------	-----------	---------	-----------	-------	-----------

MATRIX P: PROBABILITY ESTIMATES (BASED ON PRIOR DISTRIBUTIONS)

	1	2	3	4
LOW	0.2500000	0.2000000	0.1800000	0.1300000
MED	0.5000000	0.5200000	0.6000000	0.6500000
HI	0.2500000	0.2600000	0.3200000	0.3500000

THE MIDPOINT YEARS ARE

TP1	TP2	TP3	TP4	
10	25	40	TP4	55

DISCOUNTED RESULTS, IN BILLIONS OF 1975 \$:

SOCIAL DISCOUNT RATE (%)

	3	6	9	12
DELAY - PERMIT	143.4542	33.29366	8.935965	2.943876
PROHIB-PERMIT	326.3289	71.92107	17.59032	5.014822
PROHIB- DELAY	182.8747	38.62740	8.654360	2.070945

MATRIX PCS: PRIORS ON COAL SUPPLY (L,M,H)

LOW	0.2500000	MED	0.5000000	HI	0.2500000
-----	-----------	-----	-----------	----	-----------

C-4

C.2 Value Assumptions and Prior Assignments on Key Uncertainties

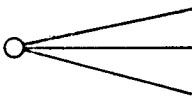
In Chapter 5, key uncertainties affecting LMFBR breeder benefits were described in Table 5.1. Of the ten key uncertainties noted, three were described earlier in Chapter 4 and Appendix B: (i) total electricity demand, (ii) nuclear capacity supply, and (iii) AET date-of-introduction. In this section, value assumptions and prior assignments on the remaining seven key uncertainties are detailed.

C.2.1 Coal-Fired Capacity Supply

Coal-generated electricity capacity supply is estimated as a function of both nuclear capacity supply and total electricity demand, expressed in terms of percent remaining electricity demand met by coal-fired plants after LWR supply is considered. The low estimate corresponds to 40% of remaining demand, medium to 70%, with high corresponding to 100% or all of the remaining demand.

1985

Coal-Generated		Low	40%
Electricity Capacity	○	Medium	70%
Supply		High	100%



Priors on coal supply are then assigned as a function of nuclear supply (A-G) and total electricity demand. Assumptions expressed in these assignments are that

- the higher the LWR supply (i.e., E-G), the more likely it is that coal will meet the remaining component of electricity demand, and
- the higher electricity demand becomes, the less likely it is that coal will meet the remaining component of electricity demand for a given LWR supply scenario.

Thus, the assignments for the case where nuclear supply is high (G) are shifted to the right of the assignments for the lower nuclear supply scenario (A) in reflection of these assumptions. Discrete approximations to the continuous assignments are given in Table C.1.

Figure C.1 Prior Assignments on Coal Electric Capacity Supply as a Function of Nuclear Supply and Total Electricity Demand (LWR Scenarios A and G; Electricity Demand H and L)

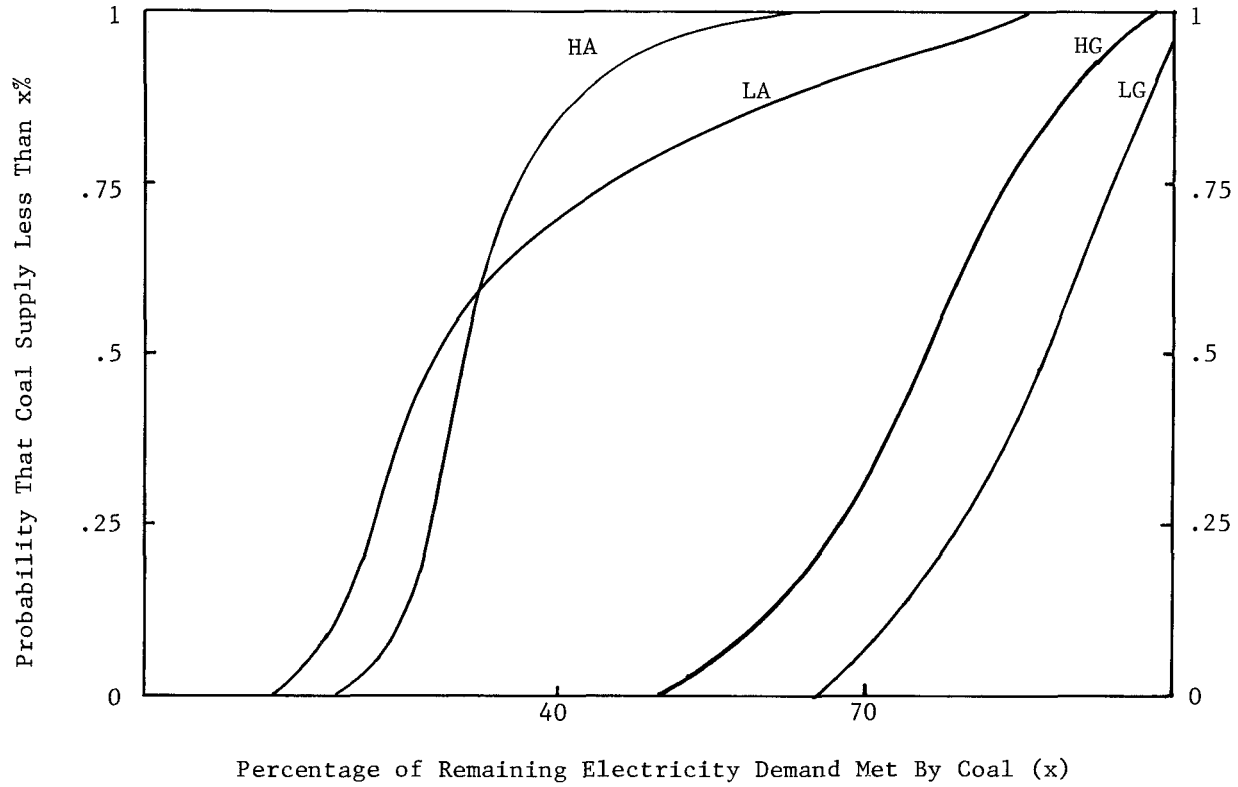


Table C.1

PRIORS ON COAL-FIRED CAPACITY SUPPLY
CONDITIONED ON NUCLEAR CAPACITY SUPPLY

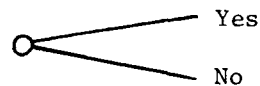
Coal Supply Scenario	Nuclear Capacity Supply (LWR)		
	A-C	D	E-G
H	0	.5	.7
M	.3	.3	.3
L	.7	.2	0

C.2.2 Swing Fuel Capacity Supply

Given the swing fuel (SWT) is available in the time period of interest, the percent of total electricity supply met by the SWT can be high (30%) or low (10%). These values were determined by noting that, during 1975, the SWT percentage was 30% and projected to drop to 25% by 1985, continuing to drop to zero by the year 2005, assuming no new oil or gas-fired capacity came on line by 1975. Otherwise, the assumption is made that the SWT is phased out by the year t^* , the introduction date of an AET.

1985

SWT Available



Based on the following projections of SWT supply as a function of time and total electricity demand, priors on SWT availability are assigned as shown in Table C.2.

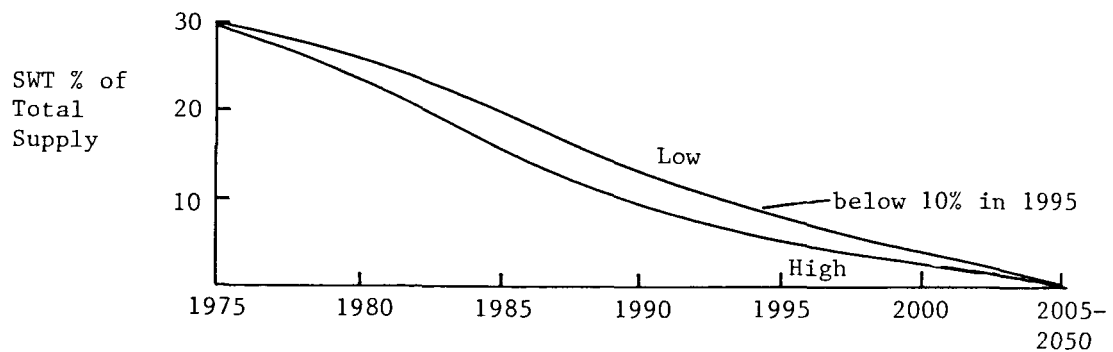


Figure C.2 Prior Distribution on Nuclear vs. Coal Generated Electricity Cost Differential (mills/kWh; 1975 \$)

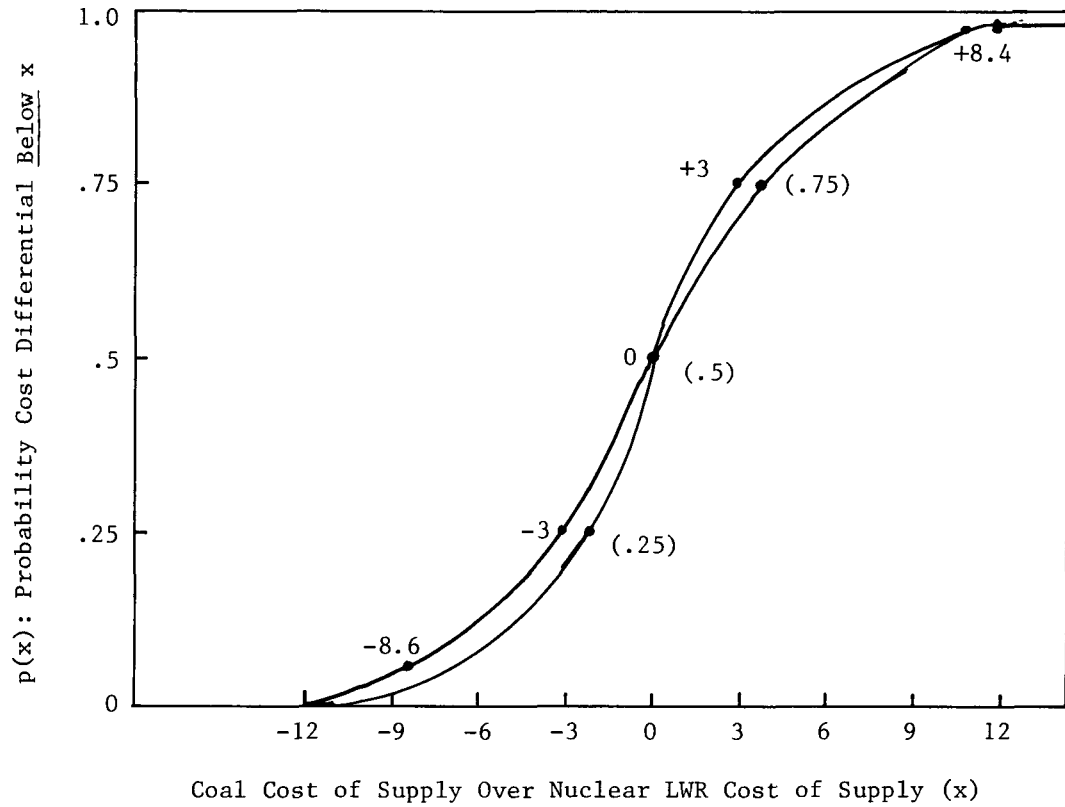


Table C.2

Priors on SWT Availability

Year	SWT Available	
	Yes	No
1975		
1985	.9	.1
1995		
2005	.5	.5
2025	.3	.7
2050	.1	.9

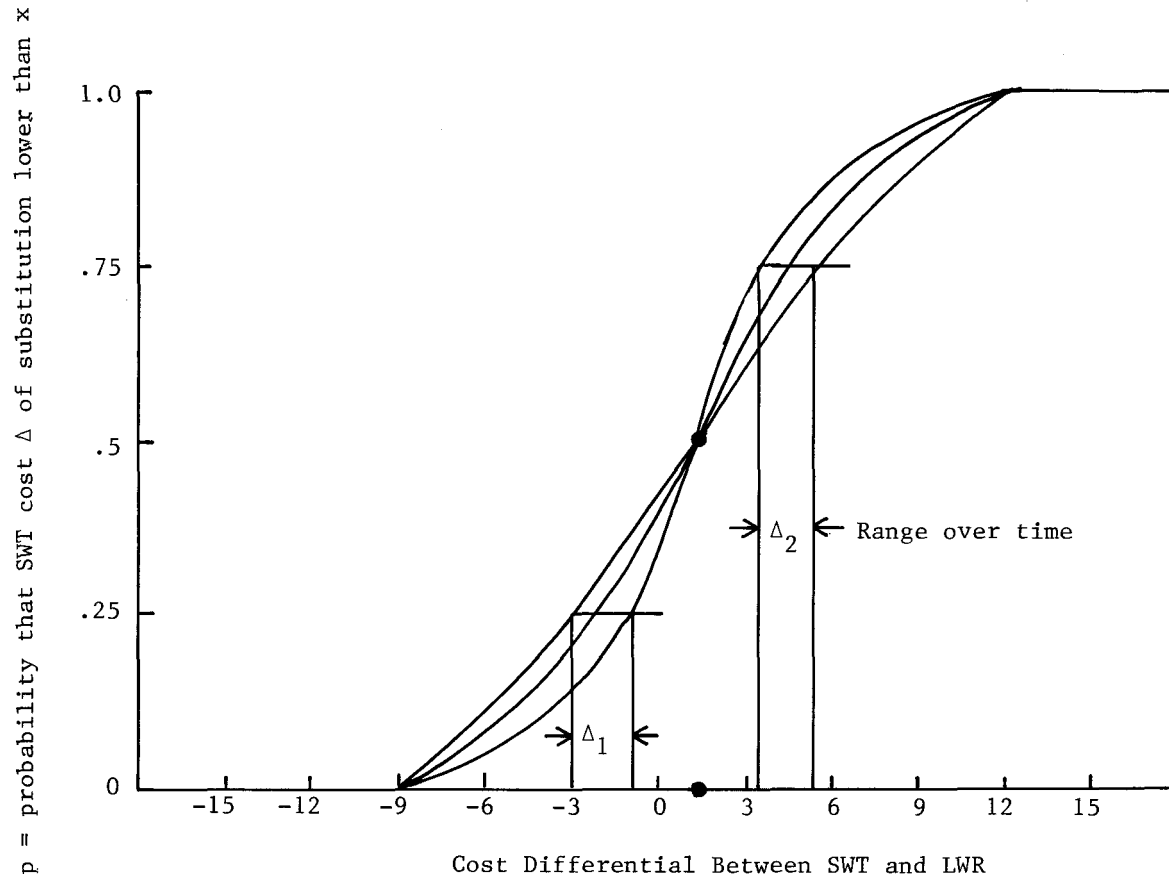
C.2.3 Coal Cost to Substitute

The coal-fired electricity cost to substitute for LWR capacity is estimated by assigning a prior distribution over a range of feasible cost differentials, measured in mills/kWh terms. The distribution is based on the data and information sources provided in Chapter 3 -- notably on a current EPRI-sponsored study [51]. Since the differential in cost between coal and LWR produced electricity varies as a function of not only plant location (i.e.,: east or west coast of U.S.), but also time, the distribution derived here is considered to represent the economy-wide case, with time causing the distribution to widen slightly, reflecting increased uncertainty (Figure C.2)¹. The maximum/minimum cost differentials are based on the following estimates:

Capital Costs + Fuel Costs \approx Total					
<u>High:</u>	Coal:	16.6	+	9	= 25.6 + 8.4 mills/kWh differential
	LWR:	14.0	+	3.2	= 17.2
<u>Low:</u>	Coal:	12.8	+	4	= 16.8 - 9.8 w/o recycle
	LWR:	19.1	+	8.5	= 27.6 - 10.8 w/o recycle
				7.5	= 26.6

¹Priors assigned are assumed relatively indifferent with respect to time, based on assumption that coal vs. LWR generating costs are so close as to be indistinguishable as time progresses in terms of absolute relative differences (see Chapter 3).

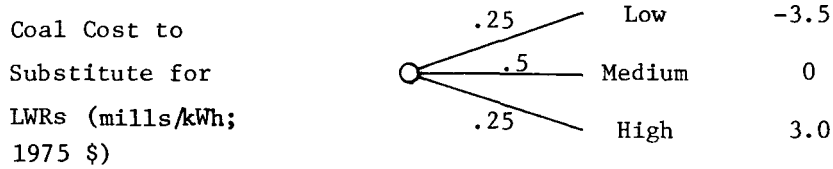
Figure C.3 Cost Differential Between SWT and LWR (mills/kWh; 1975 \$ terms)*



*Take -1 - +3.8 mills/kWh as early case and as time progresses, use -3 - +5.5 to express increasing uncertainties: Low = $\Delta_1 = -1 - -3$
 High = $\Delta_2 = +3.8 - +5.5$

The resulting discretized approximation to the continuous distribution (lottery) is:

1985



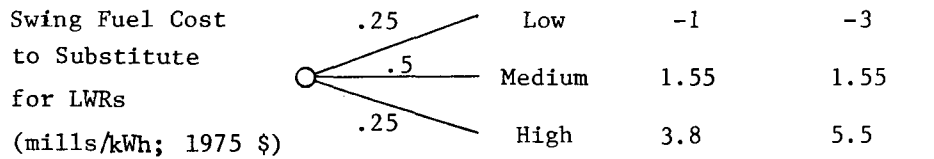
C.2.4 Swing Fuel (SWT) Cost to Substitute

As was indicated in Table 3.8 of Chapter 3, SWT fuel costs are 2-4 times greater than coal on a \$/MMBTU basis as a function of time. Therefore, the prior assignment on SWT cost differential over nuclear LWR supply is based on the following derived cost differential range (Figure C.3):

Differential	Capital Costs + Fuel Costs	≈	Total Cost	Range
SWT Low:	10.4 + 8	=	18.4 - 27.6	= - 9.2
SWT High:	13.5 + 16	=	29.5 = 17.2	= 12.3

Thus, the resulting discretized approximation is taken to be:

1995



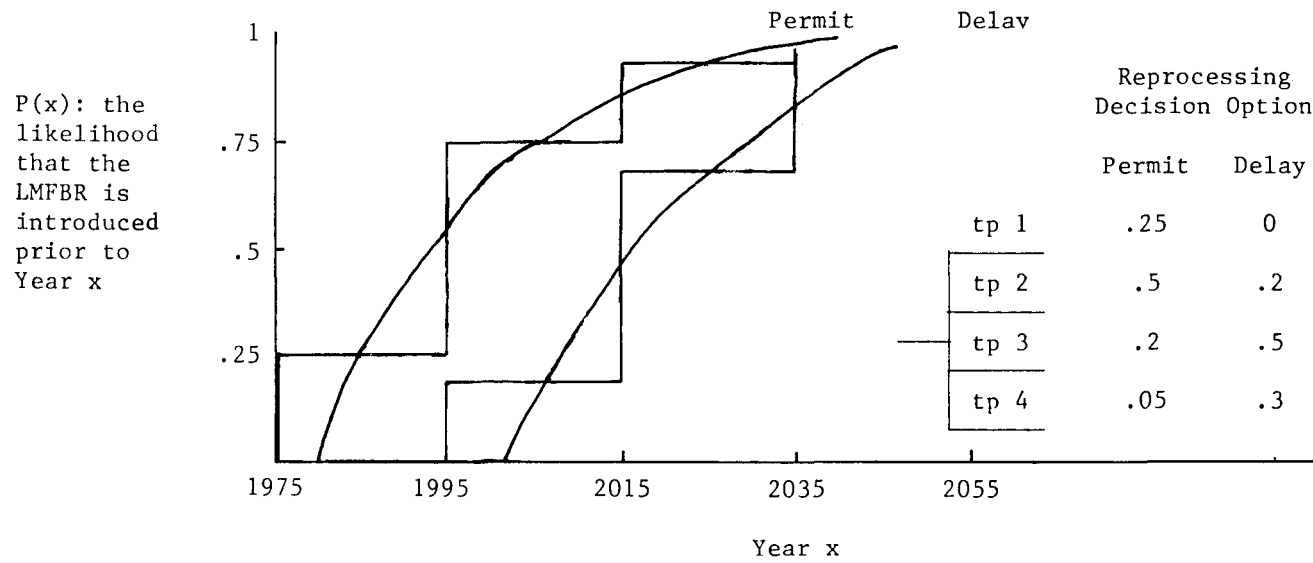
1975-1995

1996-2015

C.2.5 LMFBR Date-of-Introduction

Based on the work of R. Richels [40], it is assumed that the LMFBR introduction date reflects decisions made on R&D by the U. S. government. Additionally, it is assumed that the reprocessing decision influences the LMFBR R&D decision because the LMFBR is a reprocessing-based technology dependent upon plutonium utilization. The plutonium for initial LMFBR start-up has conventionally been thought to be derived from LWR spent fuel through reprocessing. In a sense, then, to delay reprocessing implies a

Figure C.4 Prior Distributions on LMFBR Date-of-Introduction Conditioned on Reprocessing Decision Option*

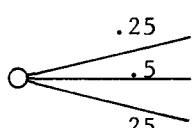


* Discrete Approximation to Continuous Prior Obtained through Maintenance of the Conditional Expected Mean within the Interval

delay of the LMFBR, since the necessary plutonium inventory and industrial infrastructure would not be available for early LMFBR start-up. Based on these considerations, the prior distributions on LMFBR start-up are given as a function of reprocessing decision alternative (Figure C.4). Note that for the prohibit option, the LMFBR is also assumed to be prohibited on the grounds that arguments used against reprocessing can also be made against the LMFBR, such that a consistent policy based on prohibition of reprocessing would necessarily imply a prohibition of the plutonium-based LMFBR.

C.2.6 LMFBR Cost to Substitute

The LMFBR will initially be more costly to build and operate than are LWRs, based on most experts' opinion as expressed in the literature. On the basis of such studies, prior distributions for the years 1995, 2005, and after 2005 are derived as shown (Figure C.5). The resulting discretized approximation to the distribution is as follows:

		<u>1995</u>	<u>2005</u>	<u>After 2005</u>
LMFBR Cost to Substitute for LWRs (mills/kWh; 1975 \$)		Low	0.4	-2.3
		Medium	1.85	1.85
		High	3.6	6.4

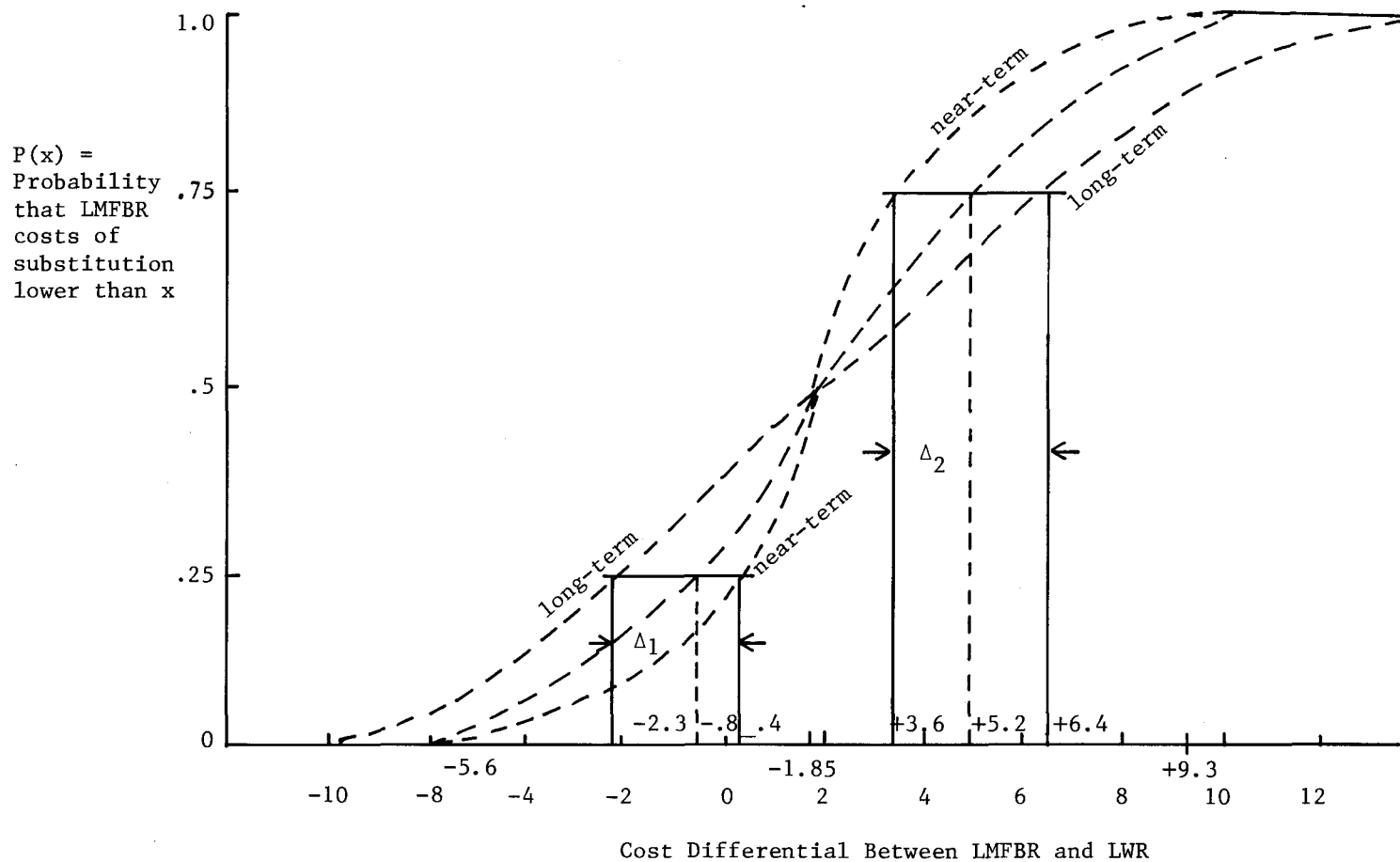
C.2.7 AET Cost-to-Substitute²

The method used to derive cost differentials between various AETs and the LWR is as follows: take the lowest generation cost projected for the AET and subtract the highest LWR generation cost to determine the lower bound on the cost differential, while reversing the calculation to establish the upper bound. The range is calculated to be (in mills/kWh; 1975 \$):

	Differential	Capital Costs	+ Fuel Costs	=	LWR	Range
AES	Low:	33.2	+	0	= 33.2 - 27.6	= 5.6
	High:	58.6	+	0	= 58.6 - 17.2	= 41.4

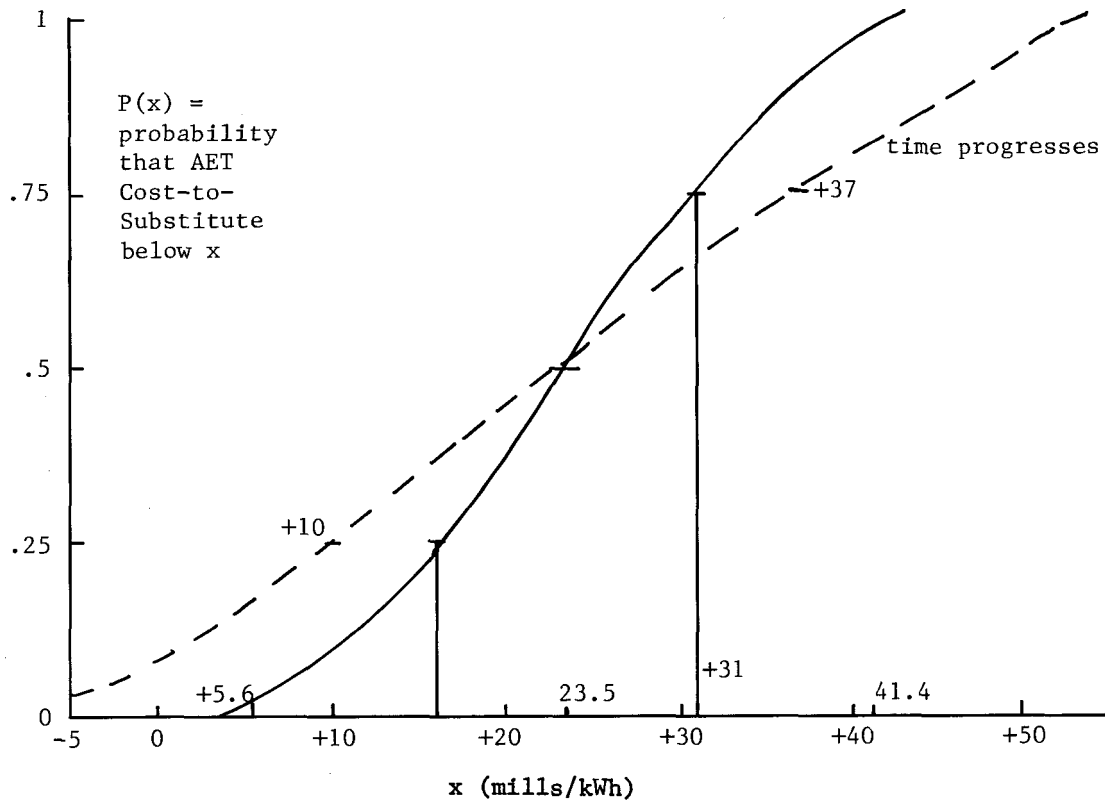
²The AET date-of-introduction is discussed in Appendix B.2.3.

Figure C.5 Prior Distributions on LMFBR Cost to Substitute for LWRs
(mills/kWh; 1975 \$ terms)



The effect of a technological "breakthrough" is thought to decrease the cost differential, moving the prior distribution to the left (Figure C.6):

Figure C.6 Prior Distribution on AET Cost-of-Substitution



The resulting discretized approximations are as follows:

AET Cost of Substitution (mills/ ; 1975 \$)	"Breakthrough"		No "Breakthrough"		EV 2005
	After 2005	2005	1995	After 2005	
.25	0 (L)		16	10	5
.5	10 (M)		23.5	23.5	16.75
.25	20 (H)		31	37	28.50

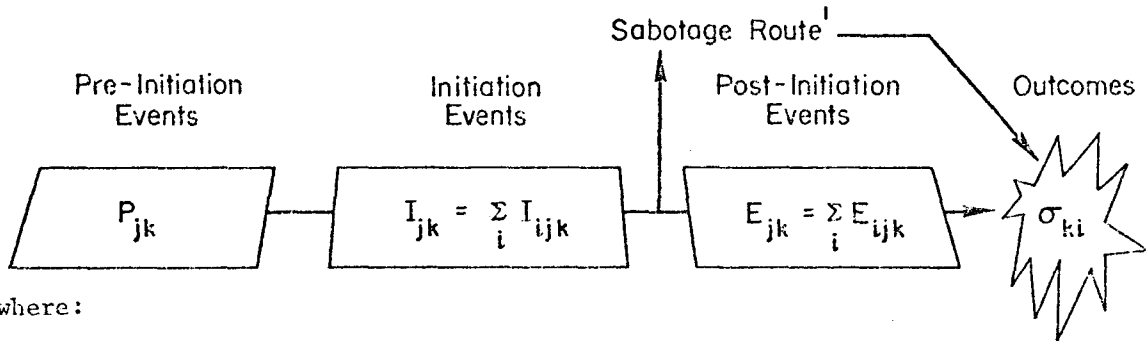
C.2.8 Economic Penalty for Supply-Restricted Demand (Under-Supply States)

The economic penalty for supply restricted demand is assumed to equal the cost of an AET at 100 mills/kWh. This assumption is made to reflect an assumed societal preference for electricity over scarcity. The determination of a more reliable estimate would be based on a careful study of society's *willingness to pay* for electricity, or, alternatively, how much would need be paid to the electricity consumer to reduce the demand to the constrained level.

Appendix D
SUPPORT CALCULATIONS FOR CHAPTER 6

D.1 Method for Quantifying Theft-Sabotage Risks

In general, a safeguards risk can be described in terms of the following sequence of events:



where:

P_{jk} = Pre-Initiation Event Likelihood that malefactors of type j will have motive k and the prerequisites to successfully carry out motive k

I_{jk} = Initiation Event Likelihood that motive k will be successfully carried out by group type j at site of attempt

$\sum_i I_{ijk}$ = sums over the number of available routes or materials i that could be used to accomplish goal k

E_{jk} = Post-Initiation Event Likelihood that malefactors of type j will successfully carry goal k to completion (refers to nuclear theft attempts)

σ_{ki} = Outcome of event with motive k using material i

Thus, the safeguard risk (R_k) associated with motive k can be expressed as:

$$(1) R_k = L_k \times \sigma_k \text{ where the likelihood } (L_k) \text{ is}$$

$$(2) L_k = \sum_j (P_{jk} \times \sum_i I_{ijk} \times \sum_i E_{ijk})$$

For nuclear theft risk (R_k^T), the expression used here is:

$$(3) R_k^T = \sum_j P_{jk} \times (\sum_i \sum_j (I_{ijk} \times E_{ijk}) \times \sigma_k^T)$$

while for sabotage (R_k^S), the expression is:

$$(4) R_k^S = \sum_j P_{jk} \times (\sum_i \sum_j I_{ijk} \times \sigma_k^S)$$

¹By definition, sabotage attempts do not involve post-initiation event sequences.

D.2 Outcome Value Assessment

Those events for which outcomes in dollar terms are assessed are sabotage, inclusive of two goal types: (i) to cause financial loss, and (ii) to cause a radiation release through accident initiation, and nuclear theft-terrorism, with three goal types: (i) to physically take over a facility or nuclear shipment in order to extort society, (ii) to acquire nuclear material for dispersal weapon purposes, and (iii) to acquire nuclear material for nuclear explosive purposes. Results and support calculations are provided in Tables D.1 - D.5.

Table D.1
ADVERSE OUTCOME VALUES (σ_{ki}) ASSOCIATED WITH RISKS

Risk Category and Description of Goal k	Outcome (σ_{ki}) in Billions of 1975 Dollars		
<p>I. Sabotage (R_k^S)</p> <p>k=1 Goal to cause financial loss</p> <p>k=2 Goal to release radio-activity through accident initiation</p>	<p>i</p> <p>1 Rep/MOX .0005-.001</p> <p>2 SURFF .0003-.0005</p> <p>1 Rep/MOX 1.14--1.65</p> <p>2 SURFF 1.2 -- 1.7</p>	<p>3 Trans. .00012</p> <p>3 Trans.</p> <p>--Fresh MOX .0004</p> <p>--N-yr Spent fuel .00074</p>	
<p>II. Nuclear Theft-Terrorism (R_k^T)</p> <p>k=1 Goal to Extort Demands Through Facility Take-over</p> <p>k=2 Goal to Acquire Material for Dispersal Weapon</p> <p>k=3 Goal to Acquire SNM for Nuclear Explosive</p>	<p>.5--1 (all facilities)</p> <p>Local Environ: 1.1</p> <p>Populated Area: 25.3</p> <p>Metropolitan Area: 60</p> <p>Suburban Area: 15</p> <p>Rural Farm Area: .3</p>	<p>EV = 50/detonation</p>	

Table D.2

OUTCOME ASSESSMENT FOR SABOTAGE

Event	Cost Contribution to Outcome Value
k=1 Financial Loss	σ_1^S = Replacement Cost for Damaged Equipment $\sigma_1^S \approx$ Capital Cost of Damaged Equipment
Notes:	<p>The outcome depends on the facility type and equipment damaged. Assumptions made on the costs of expensive equipment are as follows (1975 \$):</p> <p>--Rep/MOX Fabricator 5×10^5 -- 10^6 --SURFF 5×10^4 -- 10^5 --Transportation Vehicles 6×10^4 per vehicle</p> <p>The saboteur(s) are envisioned damaging remote handling equipment in the reprocessor/MOX fabrication facility, as this equipment is very expensive to replace. In the SURFF facility, the costs are assumed to be 10% of the costs in the reprocessor/MOX fabricator, as less expensive equipment is used in such a facility. The transportation vehicle cost is that for an armored tractor and trailer designed for MOX fuel transportation (Table H-6, [100]).</p>
k=2 Radiation Release Through Accident Initiation	σ_2^S = Cost of + Property + Evacuation + Capital Health Damage Costs Replacement Effects Costs
Notes:	<p><u>Assumptions Made:</u> (after P. Owen, [117])</p> <p>(i) Health Effects --Acute/Latent Death \$300,000/death --Serious Genetic Effect \$100,000/defect</p> <p>(ii) Property Damage --Crop Damage Area x time x 10% ROI x \$2000/acre -- Reproducible Assets Population x time x 10% ROI x \$5/person/day</p> <p>(iii) Evacuation: Population x time x \$15.50/person/day</p>

Table D.2 (continued)

Event	Cost Contribution to Outcome Value
k=2 (continued)	(iv) Plant and Equipment Capital Costs
	--Cost to Shut Down \$10 ⁶
	--Property Tax (Forever) \$6 x 10 ⁶ /year
	--Capital Cost for Facility (for 30 yrs) \$86 x 10 ⁶ /year
	(v) Total Discounted Value of Plant and Equipment \$10 ⁹

10⁹ Dollar Consequences of Major Accident
Initiated by Saboteur Explosive

Facility Type	50-Yr Man-REM	Acute Fatalities	Cancers & Genetic Effects(\$)	Acute Fatalities(\$)	Private Property & Evacuation(\$)	Plant & Equipment(\$)	Total Social Cost(\$)
Rep/MOX	-1	4-48	.04	.001-.014	.1-.6	1	1.14-1.85
SURFF	-2	4-48	.08	"	.1-.6	1	1.2-1.7
Transportation Vehicle:							
--MOX Fresh	.001	1	4x10 ⁻⁵	.0003	--	.00006	.0004
--N-Yr Spent	.002	2	8x10 ⁻⁵	.0006	--	.00006	.00074

Table D.3

OUTCOME ASSESSMENT FOR NUCLEAR THEFT -- TERRORISM

Event	Cost Contribution to Outcome Value
k=1 Nuclear Hoax	$\sigma_1^T = \text{Cost of Investigation} + \text{Cost of Disruption at Facilities}$
Principal Context Events	(a) Disrupter(s) deliver threat to nuclear facility or (b) disrupter(s) deliver threat to authorities that they have planted a nuclear explosive in populated area.
Notes:	<p>The cost of disruption for (b) will depend on: (i) the density of the population threatened and (ii) the nature of the task performed by the evacuated personnel. The disruption cost is calculated by estimating the economic effect by using average income of employee evacuated per year times the evacuation time (in years). The disruption time is assumed to be on the order of 24 hours, and the average employee's income to be \$12,000/employee-year. The number of employees affected is assumed to be on the order of the number of occupants of a typical office building (10^3-10^4 persons), where 5000 is assumed a reasonable estimate. The cost of investigation is estimated by noting that the FBI is the lead investigator in cases where threats are made involving radioactive material; by Federal statute, the nuclear aspects of threat assessment are delegated to DOE. Current assessment of a nuclear threat consists of both a technical assessment of the alleged nuclear device by the DOE and a behavioral evaluation by the FBI of the threat message and the context in which it originated. The usual approach is to rule out the possibility of a credible threat. Positive criteria for establishing that a threat is a hoax are being developed. Only in the case of a credible threat is it assumed the disruption time is greater than 24 hours (in that case, the threat is not a hoax and is covered under another event category later in these tables). The 24-hour disruption time is a conservative estimate, as normal operations would most likely resume prior to the passage of 24 hours. The cost of the evaluation and investigation of the threat is estimated by assuming 3 FBI agents at \$25,000/year are utilized, with 3 DOE professional personnel, to evaluate the threat. A total of \$10,000/hoax in operating and material costs is also assumed to cover the investigation of each threat. Under these assumptions, the outcome value per hoax has been calculated as follows:</p>

Table D.3 (continued)

Event	Cost Contribution or Outcome Value
k=1 Nuclear Hoax (continued)	<p>--Cost of Investigation = (Operating Expenses/Hoax) + (Cost of Diverting Agents to Investigate)</p> <p>= \$10,000 + \$25,000/yr x t_d x # agents</p> <p>= \$10,411/hoax</p> <p>--Cost of Disruption of Activities = \$12,000/yr/employee-person evacuated x t_d x # persons</p> <p>= \$33/day/employee x 5000 employees x 1 day</p> <p>= \$165,000/hoax</p> <p>Social Cost of Hoax = \$175,411/hoax/industry affected</p>
k=2 Dispersal	<p>O_2^T = Value of Lives Lost + Economic Replacement Cost</p> <p>= [\$300,000/life x # lives lost] + [Time Area Contaminated x Productivity/Person-Year x Population Affected (# persons)]</p>
Notes:	The following tables indicate effects of dispersal weapon planted indoors versus outdoors:

Dispersal Weapon "Yield"* (# grams)	Indoors Affected Acres (Lethal Dose)	Outdoors** Affected Acres (Lethal Dose)	Evacuation Area, Indoors	Evacuation Area, Outdoors	t_c ***
(lbs)					
(.003) 1	.124	.0025	12.4	.25	14d
(22.1) 100	12.4	.25	123.6	25	½ yr
(22.1) 10 kg	1236	25	123,600	2500	2 yr
(221) 100 kg	12,360	250	1,236,000	25,000	4 yr
(2210) 1000 kg	120,360	2500	12,360,000	250,000	10 yr

* No. of grams finely dispersed into atmosphere creating 1 hour exposure for personnel in area affected (assuming office buildings are target). From Willrich & Taylor [4].

** Assumed 50 times less hazardous than for indoors dispersal.

*** Assume time area contaminated (t_c) = 2 years for 10 kg SNM dispersed.

k=2, Dispersal

Potential # Lives Lost						
Yield (gm)	Metropolitan		Suburban		Rural/Farm	
	Indoor	Outdoor	I	O	I	O
1	19	.4	5.1	.11	.03	.0005
100	1,900	40	507	11	2.5	.05
10 kg	190,000	4,000	50,667	1,067	253	5.3
100 kg	1,900,000	40,000	500,667	10,670	2,500	53
1000 kg	19,000,000	400,000	5,006,670	106,700	25,330	530

Value of Life-Saving (\$ billions)						
Yield (gm)	Metropolitan		Suburban		Rural/Farm	
	I	O	I	O	I	O
1	.006	.00012	.0015	.00003	9×10^{-6}	1.5×10^{-7}
100	.57	.012	.152	3.3×10^{-3}	7.5×10^{-4}	1.5×10^{-5}
10 kg	57	1.2	15.2	.33	7.5×10^{-2}	1.5×10^{-3}
100 kg	570	12	152	3.3	7.5×10^{-1}	1.5×10^{-2}
1000 kg	5,700	120	1,520	33	7.5	1.5×10^{-1}

Economic Replacement Cost (\$ billions)*						
Yield (gm)	Metropolitan		Suburban		Rural/Farm	
	I	O	I	O	I	O
1	.0009	2×10^{-5}	2.4×10^{-4}	5.3×10^{-6}	1.2×10^{-6}	2.7×10^{-8}
100	.11	.002	.03	5.3×10^{-4}	1.5×10^{-4}	2.7×10^{-6}
10 kg	445	9	119	2.4	.6	.012
100 kg	8,900	178	2,373	47.5	12	.24
1000 kg	222,480	4,450	59,328	1,187	297	.59

*Metropolitan Area: $\$10^7$ - 10^9 /acre land value; \$12,000 average income; 150 persons/acre

Suburban Area: $\$5 \times 10^5$ - 2×10^6 /acre; \$12,000 average income; 40/acre

Rural/Farm Area: \$2,000/acre; \$8,000 average income; .2/acre

Total Cost (\$ billions)						
Yield (gm)	Metropolitan		Suburban		Rural/Farm	
	I	O	I	O	I	O
1 .25	.007	.00014	.0017	.000085	1.2×10^{-5}	1.8×10^{-7}
10 .25	.07	.0014	.017	.00085	1.2×10^{-4}	1.8×10^{-6}
20 .25	.14	.0028	.034	1.7×10^{-3}	2.4×10^{-4}	3.6×10^{-6}
100 .2389	.68	.014	.182	3.8×10^{-3}	9×10^{-4}	1.8×10^{-5}
10 kg .02	502	10.2	134	2.7	.6	.012
100 kg .001	9,470	190	2,525	50.8	12.8	.25
1000 kg .0001	228,180	4,570	60,848	1,220	304.5	6
Ev (I/O):	38	.76	10.1	.203	105	.001

Expected Values & Priors: (\$ billions)

	I	O	EV	Premeditated	(Lower-bound)	
					Not Premeditated	(Forced Disp)*
M	.8	.2	30.6	M	.8	0
S	.5	.5	5.2	S	.15	.2
R/F	.1	.9	.006	R/F	.05	.8

k=2, Dispersal 25.3 = EV Premeditated
 1.05 = EV Not Premeditated

* Since most facilities located in Rural/Farm Area

Table D.3 (continued)

Event	Cost Contribution to Outcome Value									
k=3 Create Nuclear Explosive for Detonation	$\sigma_3^T = \text{Value of Lives Lost} + \text{Capital Replacement Cost (for area destroyed)} + \text{Economic Replacement Cost}$ $= [\$300,000/\text{life} \times \# \text{ lives lost}] + [\text{Area (acres)} \times \text{Value/Acre}] + [\text{Population Affected (\# persons)} \times \text{time area in disuse during reconstruction and clean-up} \times \text{Productivity/ person/year}]$									
Notes:	<u>Assumptions made:</u> (i) Health Effects: Value of Life Saving \$300,000/life Serious Genetic Defect \$100,000/defect									
	(ii) Property Damage: <table style="margin-left: 40px;"> <tr> <td style="padding-right: 20px;">Value/Acre</td> <td style="padding-right: 20px;">Metropolitan</td> <td>\$10⁷-10⁹/acre</td> </tr> <tr> <td></td> <td>Suburban</td> <td>\$5x10⁵-2x10⁶/acre</td> </tr> <tr> <td></td> <td>Rural/Farm</td> <td>\$2x10³/acre</td> </tr> </table> <p>Note: Value of damaged buildings, factories, etc., inclusive of irreplaceable object value. Metropolitan area valuable because of higher density of expensive, vertical office buildings, buildings holding irreplaceable objects (art, history, etc.). Suburban values calculated assuming 10 homes per acre at \$50-200,000 per home (in 1975 \$). Rural farm value used for crop damage in WASH-1400. (Value/acre is multiplied by factor of 1/3 for moderate blast area and 1/10 for fallout area. Total destruction is assumed in severe blast area for conservative purposes.)</p>	Value/Acre	Metropolitan	\$10 ⁷ -10 ⁹ /acre		Suburban	\$5x10 ⁵ -2x10 ⁶ /acre		Rural/Farm	\$2x10 ³ /acre
Value/Acre	Metropolitan	\$10 ⁷ -10 ⁹ /acre								
	Suburban	\$5x10 ⁵ -2x10 ⁶ /acre								
	Rural/Farm	\$2x10 ³ /acre								
	(iii) Economic Replacement Cost: <table style="margin-left: 40px;"> <tr> <td style="padding-right: 20px;">--Productivity per person-year</td> <td style="padding-right: 20px;">Metropolitan</td> <td>\$12,000</td> </tr> <tr> <td></td> <td>Suburban</td> <td>\$12,000</td> </tr> <tr> <td></td> <td>Rural/Farm</td> <td>\$ 8,000</td> </tr> </table>	--Productivity per person-year	Metropolitan	\$12,000		Suburban	\$12,000		Rural/Farm	\$ 8,000
--Productivity per person-year	Metropolitan	\$12,000								
	Suburban	\$12,000								
	Rural/Farm	\$ 8,000								

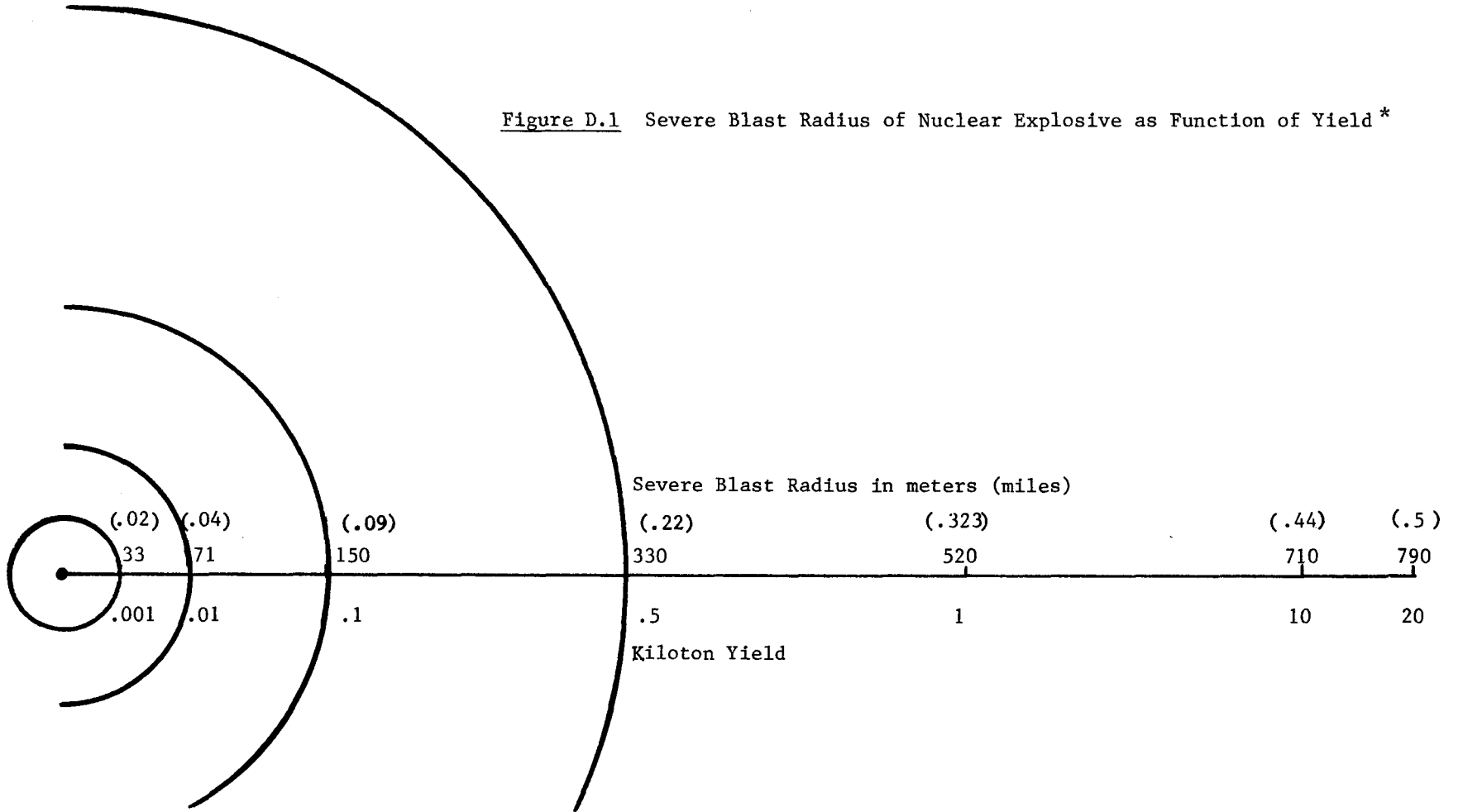
Table D.3 (continued)

Event	Cost Contribution to Outcome Value															
k=3 Create Nuclear Explosive for Detonation (Notes Cont'd)	--Time area affected: depends on yield and area type (years):															
	Metropolitan	8-12	4 - 6	2 - 3												
	Suburban	5 - 7	3 - 5	2 - 3												
	Rural/Farm	5 - 6	3 - 4	2 - 3												
		Severe Blast Area	Moderate Blast Area	Fallout Area												
Economic replacement costs represent the cost to society of replacing the goods and services produced by the affected area. This cost is estimated by defining the average per capita income, multiplying by the number of people affected and the time over which the area is in disuse.																
$\text{--Total Population Affected} = \sum_{i=1}^3 (\text{Total \# acres affected}) \times (\text{Population density/acre})_i$																
where i = 1: severe blast area; i = 2: moderate blast area; i = 3: fallout area (see Figure D.1)																
<u>Latent/Acute Deaths:</u> (i) all persons die in crater zone, (ii) 75% die in severe blast zone; 75% latent deaths, or 94% die, (iii) 35% die in moderate blast zone; of remaining total, 50% die of latent causes, or 68% assumed to die as a result of explosion, (iv) 10% acute deaths in fallout zone (assumed to extend 5 times severe blast radius); of the remaining, 10% latent deaths, or 20% die in fallout zone.																
<u>Population Densities:</u> (i) <u>Metropolitan:</u> 150/acre, (ii) <u>Suburbia:</u> 40/acre assuming 10 homes per acre with four persons/home, (iii) <u>Rural/Farm:</u> .2/acre.																
<u>Assumptions on Yield of Explosive (see Figure D.2):</u>																
<table style="margin-left: auto; margin-right: auto;"> <tr> <td style="border: 1px solid black; padding: 2px;">.25</td> <td style="padding: 2px;">100 ton</td> <td rowspan="6" style="padding-left: 20px;">(6-step approximation)</td> </tr> <tr> <td style="border: 1px solid black; padding: 2px;">.35</td> <td style="padding: 2px;">1 kT</td> </tr> <tr> <td style="border: 1px solid black; padding: 2px;">.25</td> <td style="padding: 2px;">3.3 kT</td> </tr> <tr> <td style="border: 1px solid black; padding: 2px;">.1</td> <td style="padding: 2px;">8.3 kT</td> </tr> <tr> <td style="border: 1px solid black; padding: 2px;">.03</td> <td style="padding: 2px;">13.3 kT</td> </tr> <tr> <td style="border: 1px solid black; padding: 2px;">.02</td> <td style="padding: 2px;">20 kT</td> </tr> </table>				.25	100 ton	(6-step approximation)	.35	1 kT	.25	3.3 kT	.1	8.3 kT	.03	13.3 kT	.02	20 kT
.25	100 ton	(6-step approximation)														
.35	1 kT															
.25	3.3 kT															
.1	8.3 kT															
.03	13.3 kT															
.02	20 kT															

Table D.3 (continued)

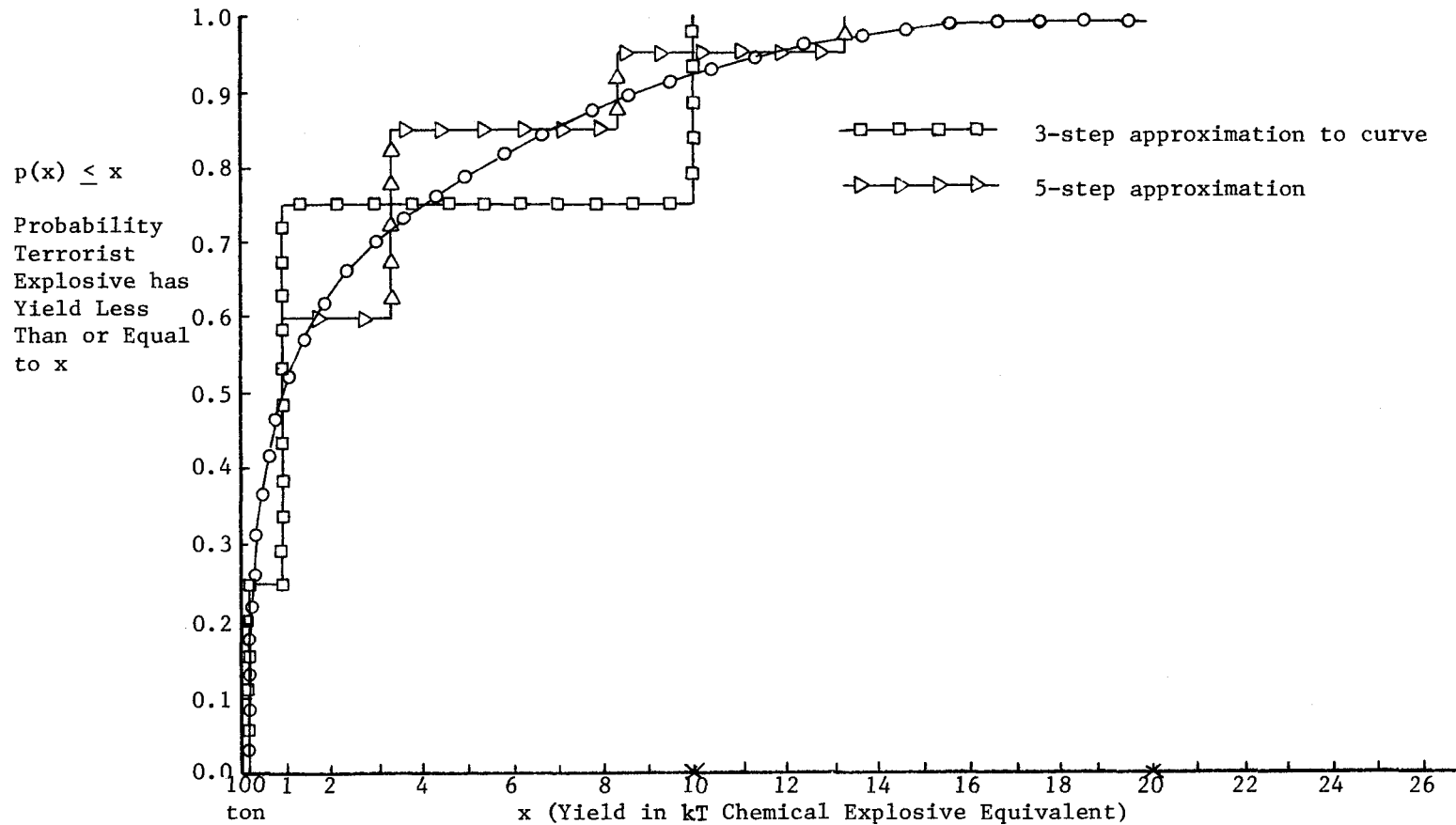
Event	Cost Contribution to Outcome Value				
k=3 Nuclear Explosive for Detonation (Notes Cont'd)	<u>Expected Value Outcomes:</u>				
	<u>Yield</u> (kT)	<u>Prior</u>	<u>Area Affected</u>		
			<u>Metropolitan</u>	<u>Suburban</u>	<u>Rural/Farm</u>
	100 ton	.25	7.6	2.0	.048
	1	.35	44.5	9.7	.22
	3.3	.25	61.8	16.3	.33
	8.3	.1	145.5	38.4	.77
13.3	.03	245	60	1.3	
20	.02	267	65.2	1.43	
EV					
M	.8	60.1			
S	.15	14.9	→ EV = 50.3 x 10 ⁹ \$ (1975)		
R/F	.05	.32			

Figure D.1 Severe Blast Radius of Nuclear Explosive as Function of Yield *



*Crater radius, in meters, for a 10 kiloton explosion is 54 m, or ~.03 miles; within the crater, all that existed is completely destroyed. Severe blast damage, assuming a peak overpressure of ten pounds per square inch, is known to cause very severe damage to almost all residential and office buildings, and moderate damage to heavily reinforced concrete buildings. Moderate blast damage of 3 pounds per square inch causes severe damage to wood frame residential buildings.

Figure D.2 Likelihood that Terrorist Explosive Will Yield a Given Kilotonage Upon Detonation*



D-13

*Based on Willrich and Taylor's implicit likelihood estimates (p. 21-22, []): "By a crude fission bomb we mean one that would have an excellent chance of exploding with the power of at least 100 tons of chemical high explosive. . . it might yield as much as 20 kilotons [upper bound], with yields ranging down to the equivalent of one ton of chemical explosive [lower bound]."

D.3 Assignment of Priors on Initiation Events

D.3.1 Pre-Initiation Events

Nine events are identified in the pre-initiation event tree (Fig. D.3). These events range from terrorist saboteur motive to cause societal harm to the malefactor's ability to gather specific information necessary to meet his objective. The assigned priors on these events are given in Table D.4, along with more detailed descriptions of the events. Finally, priors are combined to determine the relative likelihood per year that theft-sabotage attempts will be made as a function of whether or not the group has nuclear facility employees (E) involved and/or trained nuclear technologists (NC) (Table D.5). The total likelihood of sabotage-theft attempts per fuel-cycle facility per year is calculated to be 3.1×10^{-3} , where 1.1×10^{-4} is the likelihood per facility year of a theft attempt and 2.95×10^{-3} the likelihood per facility year of a sabotage event, given a probability of 1 that malefactors exist in the United States with motives to cause societal harm. The likelihood per facility year that a theft attempt would involve employee(s) and/or trained nuclear technologists was found to be $\sim 7 \times 10^{-9}$ (seven chances in one billion per facility year). For sabotage, the likelihood that an employee would be involved in an act of sabotage at the facility per year was $\sim 6 \times 10^{-4}$ (six chances in 10,000).

The importance of placing quantitative estimates on these pre-initiation likelihoods is to indicate the relative risk between attack group types, since group type influences the success likelihood of initiation and post-initiation events (i.e., the fact that one or more group members are trained nuclear technologists raises the likelihood that an explosive can be fabricated from stolen SNM in a successful fashion, given the SNM has been successfully stolen). In addition, the event tree description of theft-sabotage paths indicates explicitly the conditional nature of many of the event likelihoods that must be estimated. Thus, in order to assign realistic priors to later events appearing down the tree, it is important to carefully define pre-initiation event pathways.

Table D.4

AUTHOR'S PRIORS ON PRE-INITIATION EVENTS

Event x	Description of Event x	L(x) Likelihood per Fac.-Yr
1	Event that malefactors exist in the U.S. with motives to cause societal harm	1
2	Event that the size of a terrorist/saboteur group in the U.S. is as large as y individuals (relative likelihood)	$\frac{y}{1}$.6 8 .3 20 .1 $\Sigma=1$
3	Event that 1 or more of terrorists/saboteurs in the U.S. are employees in the backend of the U.S. commercial fuel-cycle*	$\frac{1}{1000}$
4	Event that 1 or more of the terrorists/saboteurs in the U.S. are trained, reasonably experienced nuclear chemists-technologists**	$\frac{1}{10,000}$

* Can be related to estimates on the number of potential terrorists-saboteurs that exist per total employee population (given employees are Q-cleared, psychologically tested, etc.).

** As defined by Willrich and Taylor: "The key persons or person would have to be reasonably inventive and adept at using laboratory equipment and tools of about the same complexity as those used by students in chemistry and physics laboratories and machine shops. . . would have to understand some of the essential concepts and procedures that are . . . in technical publications concerning nuclear explosives, nuclear reactor technology, and chemical explosives, and would have to know where to find these publications." (p. 21, [4]).

Table D.4 (continued)

Event x	Description of Event x	L(x) Likelihood per Fac.-Yr
5	Event that terrorists/saboteurs in the U.S. obtain general knowledge on the potential for harm by acts of sabotage or theft-terrorism in the backend of the commercial nuclear fuel-cycle	Yes 1
6	Event that terrorists/saboteurs choose to produce societal harm via backend of U.S. commercial nuclear fuel cycle (as opposed to reactors), given they have general information available	Given they are employees and/or NC: Yes .8 Given they are not employees and/or NC: Yes .01
7	Event that terrorists/saboteurs will wish to cause societal harm via theft or sabotage; relative likelihood event will be theft as opposed to sabotage	Theft .1 Sabotage .9
8	Given theft as motive, event that terrorist(s) wish to: --Build explosive --Extort society Given sabotage as motive, event that saboteur(s) wish to: --Cause maximum damage --Cause financial loss	Relative likelihoods: .1 .9 .1 .9
9	Event that terrorists/saboteurs obtain technical knowledge to be able to achieve objective	<u>Employee</u> <u>Not Employee</u> Sab. Yes 1 .5 Theft Yes 1 .1

Figure D.3 Representative Pre-Initiation Event Sequence

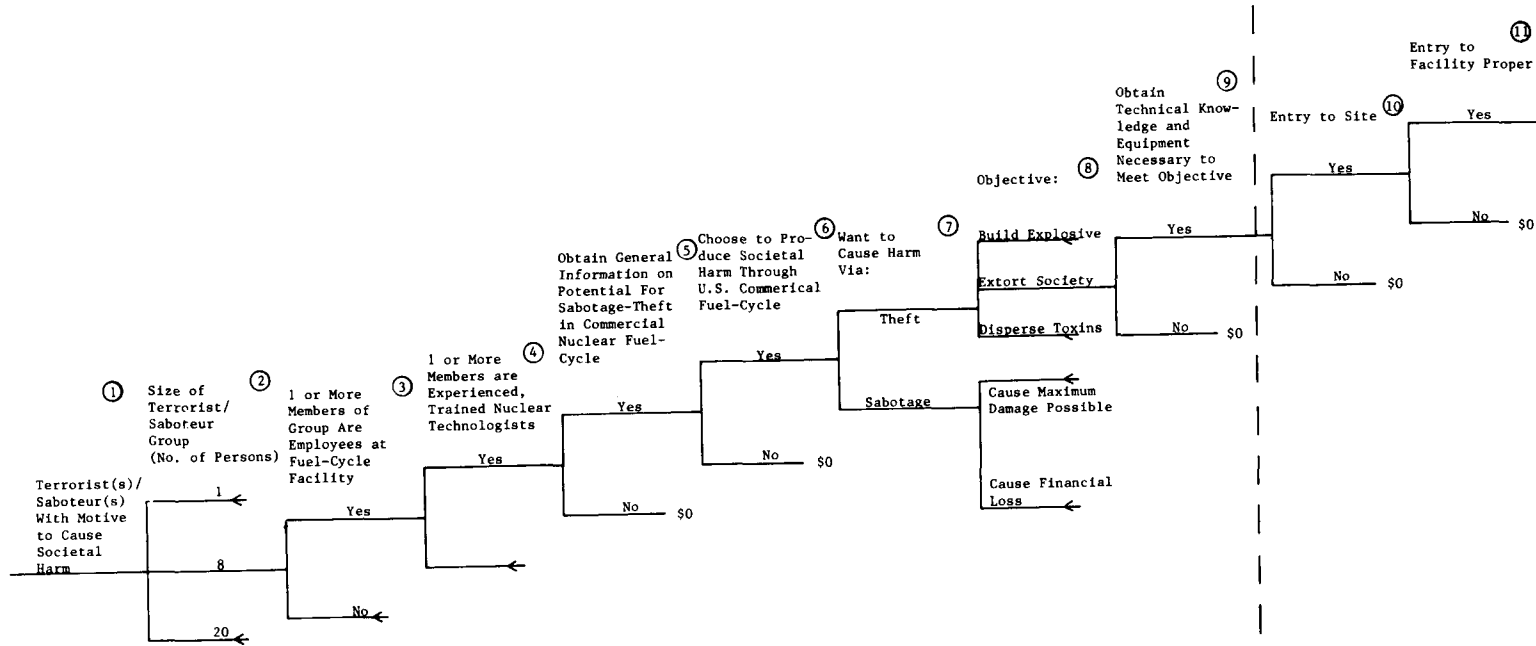


Table D.5

LIKELIHOOD PER FACILITY YEAR, PRE-INITIATION EVENTS

I. Terrorism/Theft

(a) With intent to build explosive

Event #	1	2	3	4	5	6	7	8	9	$\pi(3-9)$
\bar{NC} E	1	$\begin{pmatrix} .6 \\ .3 \\ .1 \end{pmatrix}$	$\frac{1}{1000}$	$\frac{9999}{10000}$	.8	.8	.1	.1	1	6.4×10^{-6}
\bar{E}	1	"	$\frac{999}{1000}$	"	.5	.01	"	"	.1	5×10^{-6}
\bar{NC} E	1	"	$\frac{1}{1000}$	$\frac{1}{10000}$	1	.8	"	"	1	8×10^{-10}
\bar{E}	1	"	$\frac{999}{1000}$	"	1	.8	"	"	.1	8×10^{-8}

Size of Group	\bar{NC}		NC	
	E	\bar{E}	E	\bar{E}
1	3.84×10^{-6}	3×10^{-6}	4.8×10^{-10}	4.8×10^{-8}
8	1.92×10^{-6}	1.5×10^{-6}	2.4×10^{-10}	2.4×10^{-8}
20	6.4×10^{-7}	5×10^{-7}	8×10^{-11}	8×10^{-9}
$\Sigma =$	6.4×10^{-6}	5×10^{-6}	8×10^{-10}	8×10^{-8}

(b) With intent to extort society using SNM directly

$$\begin{array}{rcl}
 \bar{NC} \text{ E} & 3.8 \times 10^{-5} & \\
 \bar{E} & \underline{3 \times 10^{-5}} & \\
 & 7 \times 10^{-5} & \times .4 = 2.8 \times 10^{-5} \\
 NC \text{ E} & 4 \times 10^{-9} & \\
 \bar{E} & 4 \times 10^{-7} &
 \end{array}$$

Table D.5 (continued)

(c) With intent to distribute stolen SNM into environment as toxin:

$$\begin{array}{ll} \bar{NC} \ E & 1.9 \times 10^{-5} \\ \bar{E} & 1.5 \times 10^{-5} \end{array} \qquad \begin{array}{ll} NC \ E & 2 \times 10^{-9} \\ \bar{E} & 2 \times 10^{-7} \end{array}$$

II. Sabotage

(a) With intent to cause maximum damage*

Event #	1	2	3	4	5	6	7	8	9	
$\bar{NC} \ E$	1	$\begin{pmatrix} .6 \\ .3 \\ .1 \end{pmatrix}$	$\frac{1}{1000}$	$\frac{9999}{10000}$	.8	.8	.9	.1	1	5.8×10^{-5}
\bar{E}	1	"	$\frac{999}{1000}$	"	.5	.01	.9	"	.5	2.3×10^{-4}
$NC \ E$	1	"	$\frac{1}{1000}$	$\frac{1}{10000}$	1	.8	.9	"	1	7.2×10^{-9}
\bar{E}	1	"	$\frac{999}{1000}$	"	1	.8	.9	"	.5	3.6×10^{-6}

*Independent of whether NC included in group or not; in the sabotage case, the more crucial element is whether or not an employee is in the group

$$TOTAL \ E = 5.8 \times 10^{-5} \qquad \bar{E} = 2.34 \times 10^{-4}$$

(b) With intent to cause financial loss

$$\begin{array}{ll} \bar{NC} \ E & 5.22 \times 10^{-4} \\ \bar{E} & 2.1 \times 10^{-3} \end{array} \qquad \begin{array}{ll} NC \ E & 6.5 \times 10^{-8} \\ \bar{E} & 3.2 \times 10^{-5} \end{array} \qquad \begin{array}{ll} TOTAL \ E & 5.22 \times 10^{-4} \\ \bar{E} & 2.132 \times 10^{-3} \end{array}$$

D.3.2 Initiation Events

Representative initiation event sequences for nuclear theft and sabotage attempts are given for: (i) the reprocessor/MOX fabrication facility versus SURFF facility, and (ii) transportation of fresh MOX fuel versus N-year old spent fuel (Figures D.4-9). The primary adversary categories considered are the single employee become saboteur and the moderate-to-large armed terrorist group. These two adversary categories have been identified as the most potentially dangerous threats to the nuclear fuel cycle (see BDM report, [93]).

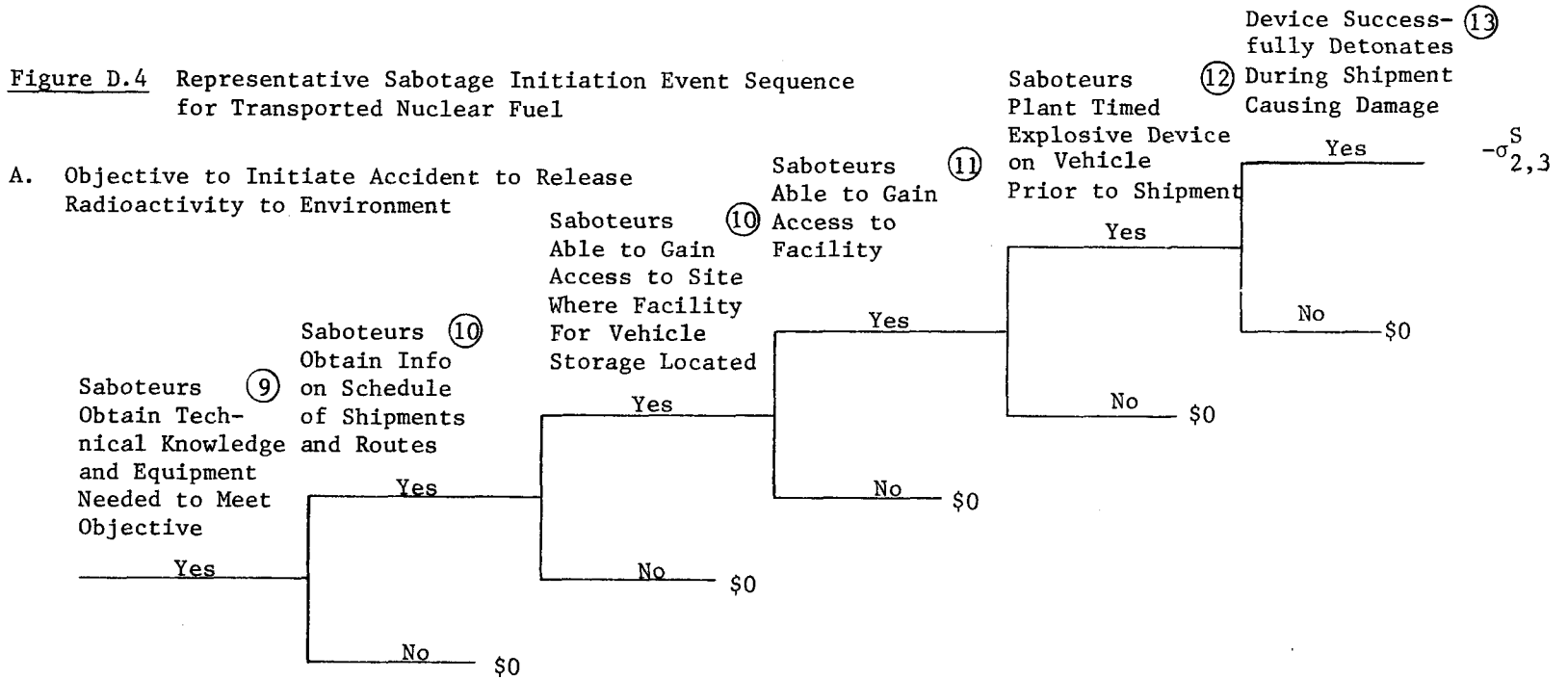
The first obstacle a would-be terrorist or saboteur faces in carrying out their objective is gaining access to the site of the facility and then to the facility itself (events 10 and 11). The probability of gaining access depends on the security at the site. Nuclear fuel cycle facilities are required both by domestic law and international agreement to be physically safeguarded (see "Structure and Content of Agreements between the IAEA and States Ratifying the NPT," (INCFCIRC/153)). Such safeguard plans include armed guard forces, lighted barriers around the site perimeter, close liaison and communications with local law enforcement agencies and restrictions on visits. Most of the current (as of 1978) security plans are based on the detection of intruders at the perimeter of the plant with alarms, cameras, etc. monitored from one or more of the guard houses on the site. However, the guards at the facility are not expected to offer significant resistance against a well armed terrorist group unless specifically trained for such purposes. It was assumed that the armed adversary group would gain entry to the site with probability .3 for an untrained guard force, and .03 for a trained guard force on the site (see Owen, [117]). In the case of the single adversary assumed to be facility employee, a probability of 1 was assigned for these events.

Access to the facility proper (event 11) would be met by locked doors and restricted access to areas. Assuming all guards were overcome upon the terrorist group intrusion onto the site, the likelihood of a successful entry to the facility proper is assumed to be on the order of .5. For a single employee, the likelihood of a successful entrance to the facility proper is again assumed 1. However, the likelihood that a

single employee would be able to gain access to expensive equipment and successfully damage it without apprehension (event 24) is thought to be low because of the high probability that the employee would be apprehended by guards and/or other employees before being able to cause significant financial loss. However, a large group of armed saboteurs is assumed to be able to gain access to expensive equipment with a 50-50 chance of being successful in causing financial damage. With regard to initiating an accident to release radioactivity to the environment (event 12), the likelihoods are assumed low because of the 2-3 hour time limit required to plant an explosive to initiate the accident [117]. However, for the case of the single employee working alone, the likelihood is assumed higher.

Descriptions of other significant events and their assigned representative likelihoods are shown in Table D.6.

Figure D.4 Representative Sabotage Initiation Event Sequence for Transported Nuclear Fuel



B. Objective to Cause Financial Loss

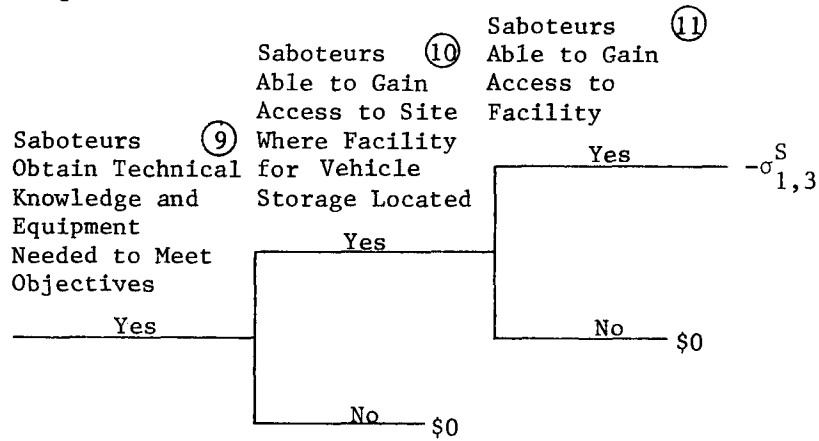


Table D.6

INITIATION EVENTS, LIKELIHOOD PER FACILITY YEAR

Event x	Description of Event x	L(x) Likelihood per Fac.-Yr
10	Event that entry to site of U.S. commercial fuel cycle facility is successful without detection, apprehension or restriction by authorities	Terrorist Group .3 Average guard force .03 Well-armed guard force Single Employee 1
11	Event that entry to facility proper is successful	Terrorist Group .5 Single Employee 1
10'	Event that terrorists obtain information on schedule of shipment and route	.5
11'	Event that terrorists overcome armed guards following shipment in two escort vehicles	10 ⁻²
12'	Event that terrorists overcome drivers before radio communication made with national command centre	10 ⁻³
13'	Event that terrorists overcome drivers before automatic alarm is detonated notifying recovery force	10 ⁻³
14'	Event that driver unable to detonate device to destroy truck engine in time to prevent terrorists from driving away with cargo	10 ⁻³
15'a	Event that terrorists able to drive away with cargo before being apprehended	Yes .9 No .1

Table D.6 (continued)

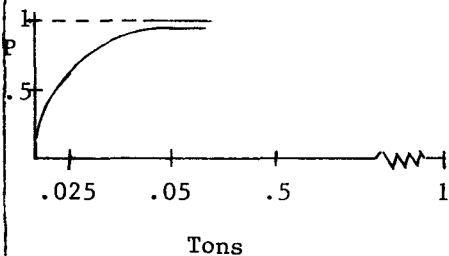
Event x	Description of Event x	L(x) Likelihood per Fac.-Yr
15b'	Event that terrorists able to breach trailer armed to level 4 intrusion resistance with walls 3" thick	Yes 10^{-4}
16b'	Event that terrorists overcome poison gas, protective foam and other materials protecting cargo	Yes 10^{-4}
17b'	Event that terrorists lift assemblies through access hole to awaiting vehicle without harm to themselves	Yes 10^{-4} Fresh MOX Fuel 10^{-5} N-yr Spent Fuel
18'	Event that terrorists drive to hideaway laboratory with cargo in terrorist vehicle without apprehension	10^{-1} Fresh MOX Fuel 10^{-3} N-yr Spent Fuel
12	Saboteurs plant timed explosive device Probable yield of explosive device; assumed chemical explosive 	\bar{E} .5 E .1 Fresh MOX Fuel
13	Device successfully detonated during shipment	E .5 \bar{E} .1

Table D.6 (continued)

Event x	Description of Event x	L(x) Likelihood per Fac.-Yr
15	Gain access to hoist machinery (it is assumed extremely likely that the saboteur could gain access to the hoist machinery once inside the facility)	.9
16	Hoist fuel out of pond successfully (assumes hostage could be used to operate machinery or saboteur himself could do so without setting off safety lock device on crane)	.05
17	Decide to disassemble fuel assembly for easy handling (assumes that it would be more likely that the terrorists would avoid using time to disassemble the fuel assembly, which weighs 1/2 a ton, but would instead hoist it directly into a waiting carrier (such as a vehicle suitable or fork lift truck) to remove it off site)	<p>N-yr Spent Fuel fresh fuel (MOX)</p> <p>Y .1 Y .5</p> <p>N .8 N .5</p>
18	Transport off site successfully; assumed more likely to be successful in case of fresh fuel because of its lower radioactivity and health hazard	<p>N-yr Spent Fuel</p> <p>Y .5</p>
19	Transport to clandestine lab successfully (assumes that, because of neutron radiation, spent fuel is more easily detectable than are fresh MOX, PuO ₂ powder or Pu nitrate solution.	<p>N-yr Spent Fuel .5</p> <p>fresh fuel, PuO₂, Pu (NO₃)₂ .9</p>
20	Disperse material into local environment when apprehended	.5
21/22	Gain access to reprocessing area as opposed to MOX fuel processing area	Rep. .9

Table D.6 (continued)

Event x	Description of Event x	L(x) Likelihood per Fac.-Yr
23	Terrorists are successful in stealing: a) PuO_2 from surge tank in powder form b) $\text{Pu}(\text{NO}_3)_2$ in liquid form c) PuO_2 pellets d) MOX fuel	 .05 .05 .1 .05
24	Gain access to expensive equipment (assumes once saboteur gains access to equipment, he can always cause its destruction through use of tools or explosives)	Y .5 N .5

Figure D.5 Initiation Events: Representative Theft Event Sequences for Transported Nuclear Fuel Assemblies (Primed Events)

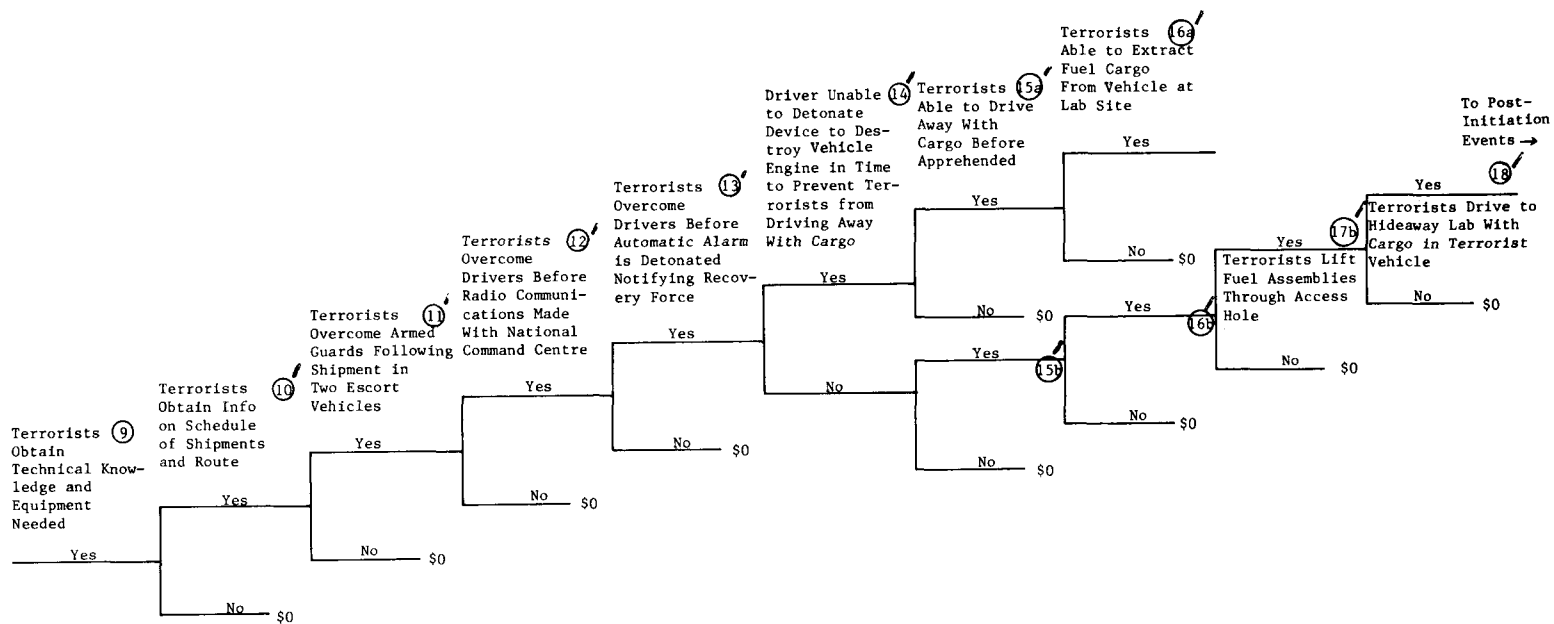


Figure D.6 Comparative Theft Event Sequences for Reprocessor/MOX Fabricator vs. Spent Fuel Temporary Storage Repository

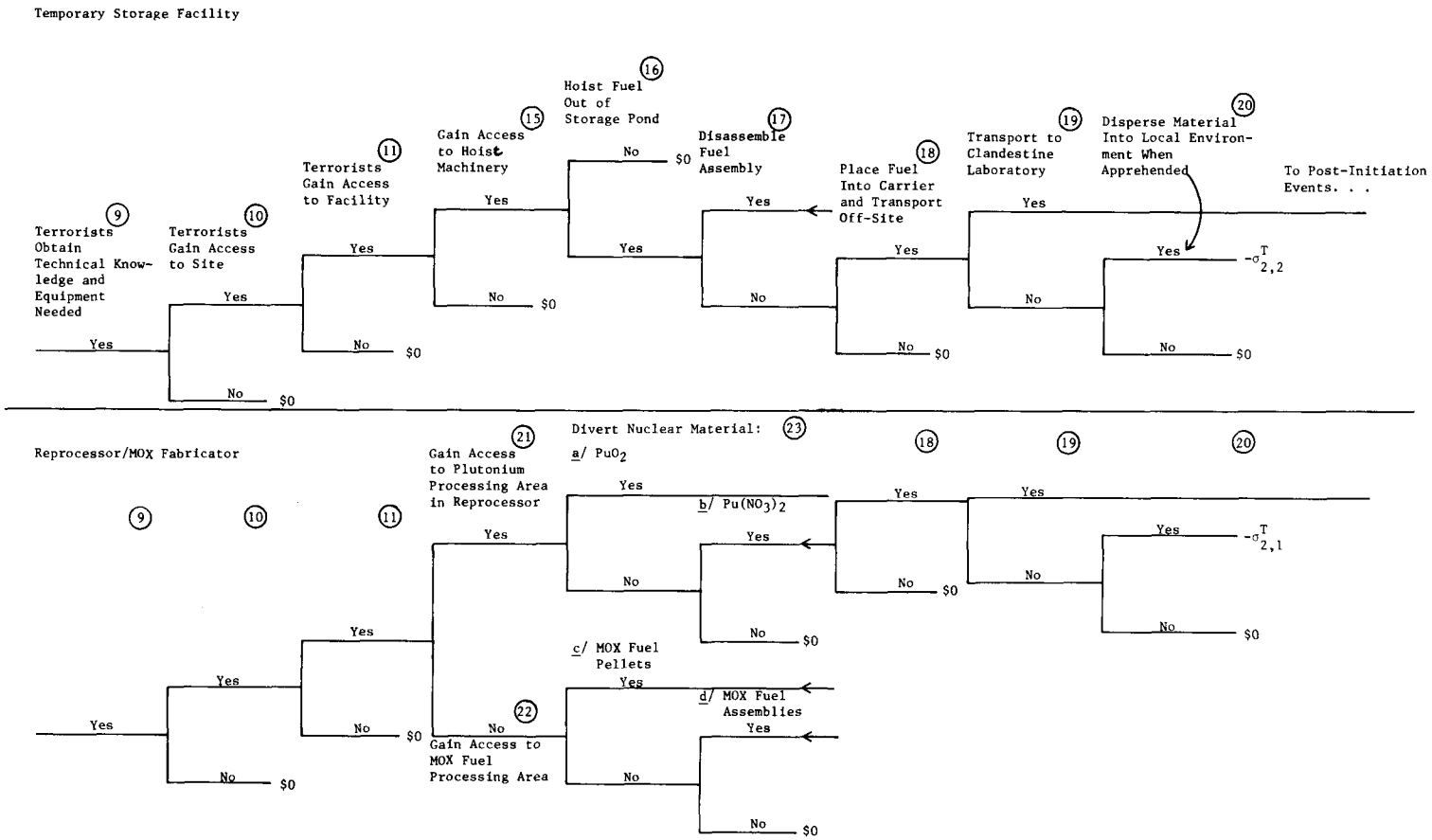
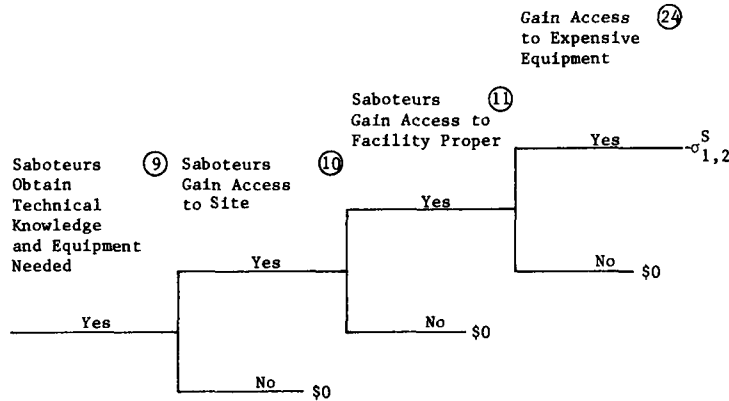


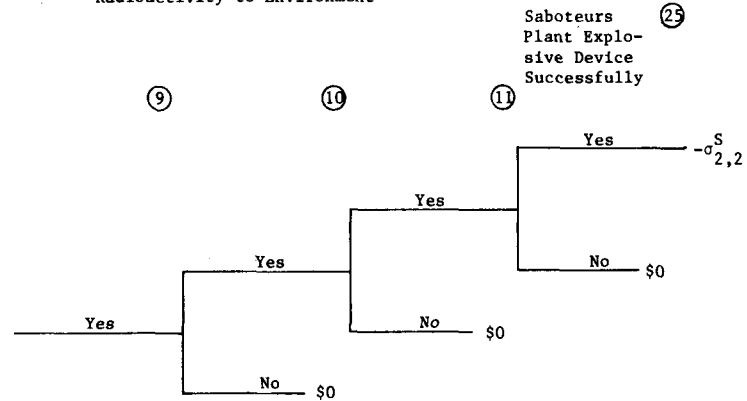
Figure D.7 Comparative Sabotage Initiation Events : Reprocessor/MOX' Fabricator
Versus N-Yr Old Spent Fuel Temporary Storage Repository

1. Temporary Storage Facility

A. With Motive to Cause Financial Loss

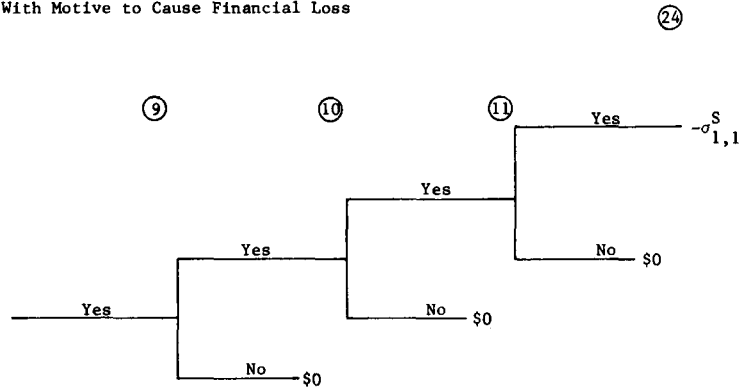


B. With Motive to Initiate Accident to Release Radioactivity to Environment

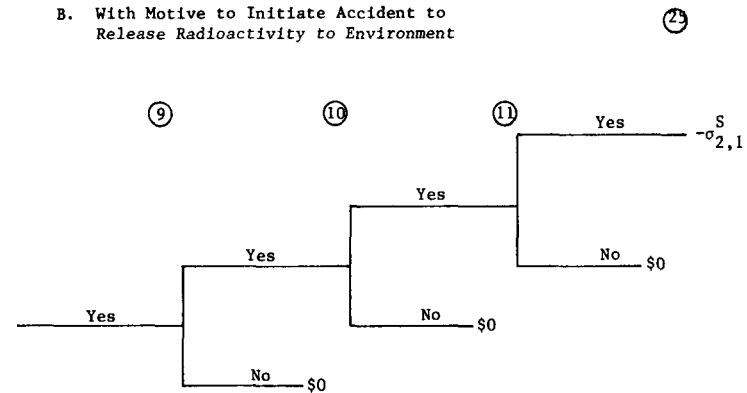


2. Reprocessor/MOX_x Fabricator

A. With Motive to Cause Financial Loss



B. With Motive to Initiate Accident to Release Radioactivity to Environment



D.3.3 Post-Initiation Events

A series of events are identified in the post-initiation event tree (Figure D.8). The first event pertains to a situation where terrorists steal nuclear fuel. Unless the reprocessing of the fuel takes place, the PuO_2 cannot be separated out to make a dispersal weapon or nuclear explosive. Given PuO_2 is made available, the terrorists have the option of converting it into a metallic form so that more efficient weapons with higher probability of reaching a design yield can be built using less plutonium by weight or compacting the PuO_2 powder directly into the appropriate explosive shape. Each of these stages takes time; the success likelihoods assigned in the following tables reflect the likelihood of such operations proceeding without apprehension or intervention by authorities. It is evident that because clandestine reprocessing takes a relatively long time to perform (on the order of 3-4 months for a moderately well-equipped and trained group), the likelihood that spent fuel, MOX pellets or fresh fuel can be successfully processed to extract SNM is quite low. However, because fresh MOX is more easily handled (if not "spiked" with gamma emitters for protective purposes), the likelihood assigned to the fresh MOX case is substantially higher than for the spent fuel case (Table D.7).

The remainder of the event likelihoods are assigned based on timing considerations; it is assumed that the terrorists will choose to go the oxide route 9 out of 10 times to save time, given they have adequate material (from 35-90 kg of PuO_2). For the dispersal weapon, PuO_2 could be used directly. After this step, event 4, 5, 8, and 10 are assessed to take relatively less time and effort to perform successfully given the other components of the weapon have been pre-assembled and are awaiting only the fission trigger to make them complete. In the case of event 10, it is assumed that one out of every ten attempts would be made without a warning being given to the targeted populace; in that case, no evacuation is assumed, and the explosive is assumed to be detonated at surface level causing the maximum damage possible. With evacuation, the consequences of the explosion are less.

The set of consequences indicated by the letter z refer to the case where the terrorists either choose not to manufacture explosives, or

are foiled in their attempts to do so (Table D.8). The consequences are expressed as the expected value consequence of dispersal and/or extortionist attempts that the terrorists might pursue either during apprehension or in lieu of manufacturing explosives. In the case where dispersal is a result of apprehension, it is assumed equally likely that the SNM will be dispersed successfully to the local environment surrounding the clandestine laboratory (as opposed to not being dispersed). Consequences are as calculated in Table D.9.

The results of "folding-back" the post-initiation event sequences under these assumptions are given in Table D.10 as a function of material type and terrorist motive.

Figure D.8 Post-Initiation Events: Theft with Intent to Construct Explosive

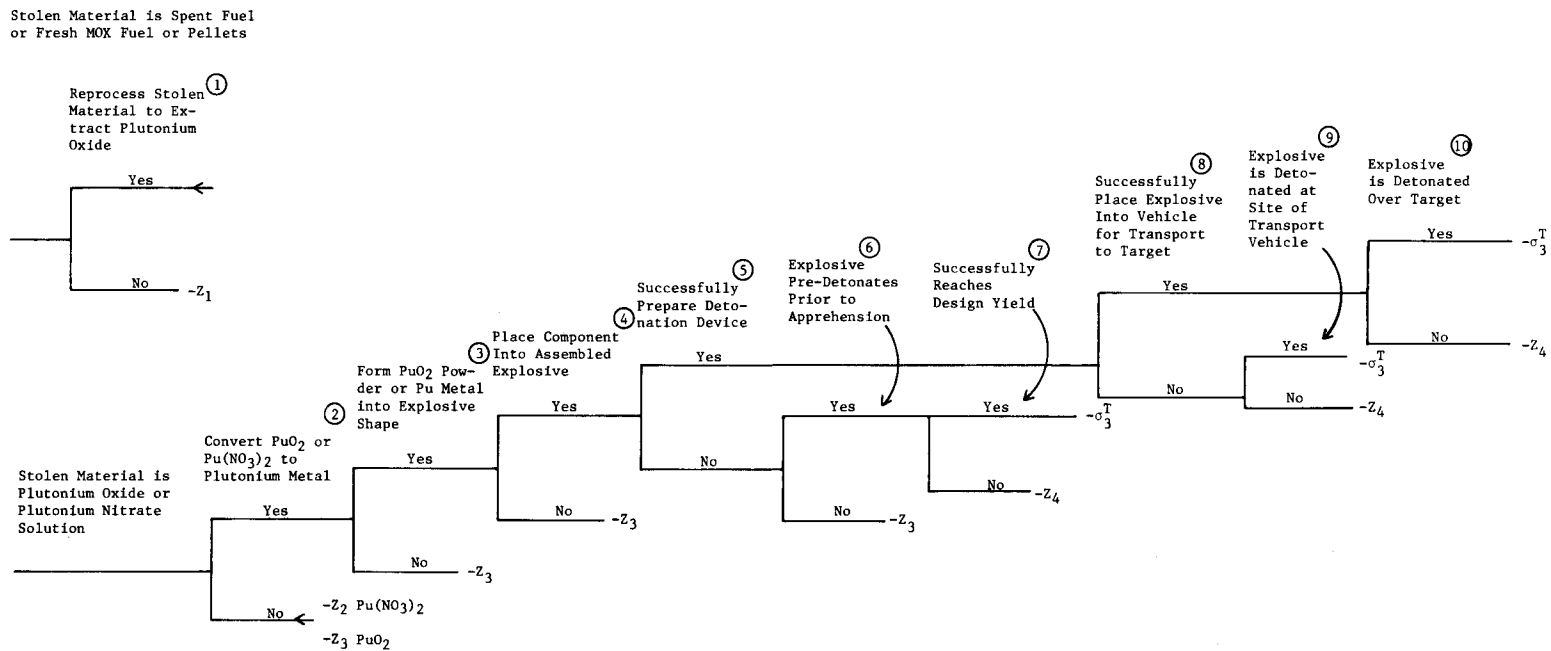


Table D.7

POST-INITIATION EVENTS, LIKELIHOOD PER FACILITY YEAR

Event x	Description of Event x	L(x) Likelihood per Fac.-Yr									
1	Event that stolen nuclear fuel can be reprocessed by nuclear terrorists in a successful fashion without apprehension by authorities	N-yr Old Spent Fuel 10^{-3} Fresh MOX Fuel 10^{-2}									
2	Event that extracted/stolen PuO_2 - $\text{Pu}(\text{NO}_3)_6$ is converted to metal without detection by authorities or mishap, so that more efficient weapons can be manufactured	<table border="0"> <tr> <td></td> <td>$\text{Pu}(\text{NO}_3)_6$</td> <td>PuO_2</td> </tr> <tr> <td>Yes</td> <td>.5</td> <td>.01</td> </tr> <tr> <td>No</td> <td>.5</td> <td>.99</td> </tr> </table> <p>(Since is easier to convert $\text{Pu}(\text{NO}_3)_6$ to metal than to convert it to oxide, and is easier to convert $\text{Pu}(\text{NO}_3)_6$ to metal than to convert PuO_2 to metal [60])</p>		$\text{Pu}(\text{NO}_3)_6$	PuO_2	Yes	.5	.01	No	.5	.99
	$\text{Pu}(\text{NO}_3)_6$	PuO_2									
Yes	.5	.01									
No	.5	.99									
3	Event that terrorists use PuO_2 directly or Pu metal to form Pu into shape for explosive use	<table border="0"> <tr> <td></td> <td>Yes</td> <td>No</td> </tr> <tr> <td>Sufficient PuO_2</td> <td>.9</td> <td>.1</td> </tr> <tr> <td>Insufficient PuO_2</td> <td>.1</td> <td>.9</td> </tr> </table>		Yes	No	Sufficient PuO_2	.9	.1	Insufficient PuO_2	.1	.9
	Yes	No									
Sufficient PuO_2	.9	.1									
Insufficient PuO_2	.1	.9									
4	Event that terrorists, without detection, place fissionable component into ready made nuclear bomb without mishap	<table border="0"> <tr> <td>Yes</td> <td>.9</td> </tr> <tr> <td>No</td> <td>.1</td> </tr> </table>	Yes	.9	No	.1					
Yes	.9										
No	.1										

Table D.7 (continued)

Event x	Description of Event x	L(x) Likelihood per Fac.-Yr
5	Event that terrorists are able to prepare device to avoid predetonation after it is assembled	Yes .9 No .1
6	Event that one of the weapons made by terrorists predetonates prior to successful detonation over target	Yes .1 No .9
7	Event that weapon reaches design yield given it predetonates	Yes .1 No .9
8	Event that terrorists are able to place constructed nuclear bombs into vehicles for transportation to societal target without detection	Yes .9 No .1
9	Event that weapon is exploded successfully given terrorists are apprehended when loading transport vehicles	Yes .5 No .1
10	Event that weapons are detonated over targets successfully	Yes .9 No .1
11	Convert nitrate solution to oxide successfully (without detection and apprehension)	Yes .8 No .2
12	Successfully construct disposal weapon	Yes .8 No .2
13	Successfully disperse material through use of dispersal weapon	Yes .8 No .2
14	Successfully extort society	Yes .9 No .1

Figure D.9 Post-Initiation Events: Theft with Intent to Construct Dispersal Weapon

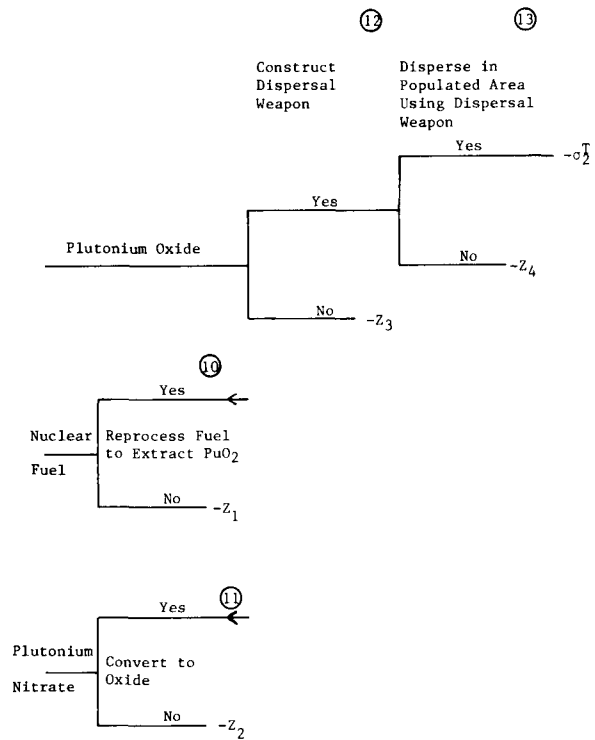


Figure D.10 Post-Initiation Events: Theft with Intent to Extort Society

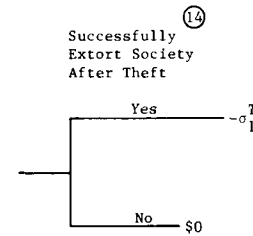


Table D.8

ANALYZING DISPERSAL/EXTORTION POST-INITIATION EVENTS--
DIFFERENCES BETWEEN N-YR OLD SPENT FUEL AND FRESH MOX FUEL

Event x	Description of Event x	L(x) Likelihood per Fac.-Yr								
Z	Broken down into X and Y: event could take place several places along the event tree; likelihoods are assumed to remain the same independent of the point in the tree at which event Z occurs; the outcomes do, however, depend on where, and in what form, the SNM is dispersed									
X	Event that SNM is dispersed successfully to the environment --When group is apprehended while pursuing other motives --When group desires to disperse SNM rather than use in nuclear weapon	<table border="0"> <tr> <td>Yes</td> <td>.5</td> </tr> <tr> <td>No</td> <td>.5</td> </tr> <tr> <td>Yes</td> <td>.9</td> </tr> <tr> <td>No</td> <td>.1</td> </tr> </table>	Yes	.5	No	.5	Yes	.9	No	.1
Yes	.5									
No	.5									
Yes	.9									
No	.1									
Y	Event that terrorists use SNM to extort society successfully once they are subverted from completing their original plans	<table border="0"> <tr> <td>Yes</td> <td>.5</td> </tr> <tr> <td>No</td> <td>.5</td> </tr> </table>	Yes	.5	No	.5				
Yes	.5									
No	.5									

Table D.9

CALCULATION OF OUTCOME Z

$$Z = P_y^Y \cdot P_x^N \cdot -\sigma_{1,i}^T + P_x^Y \cdot -\sigma_{2,i}^T$$

= Probability of Successful Extortion · Unsuccessful at Dispersing in Environment · Social Cost of Extortion + Successful at Dispersing in Environment · Social Cost of Dispersal of Material in its Form at Time of Apprehension

i	10 ⁹ \$	Extortion			Dispersal		
	Z = $\frac{.27-.6}{.25-.58}$	P_y^Y	P_x^N	$-\sigma_{1,i}^T$	P_x^Y	$-\sigma_{2,i}^T$	
Spent Fuel or Fresh MO _x	1	.27-.6 .25-.58	.5	.5	1-2.3x10 ⁹\$	.5	10x10 ⁶ 5x10 ⁶
Pu (NO ₃) ₂	2	.25-.58	.5	.5	"	.5	1x10 ⁶
PuO ₂	3	.29-.61	.5	.5	"	.5	70x10 ⁶
Dispersal Weapon	4	22.9	.5	.1	"	.9	25.3x10 ⁹ *

Table D.10

POST-INITIATION EVENTS: EXPECTED VALUE OUTCOMES (10⁹ \$, 1975 terms)*
(Summary Table)

Incident Type	Type of Nuclear Material Stolen			
	Pu Oxide	Pu Nitrate Sol'n.	MOX Fuel or Pellets**	N-Yr Spent Fuel
Theft with Intent to Construct Dispersal Weapon	Suc. 16.2	12.8	.16	.016
	No Suc. 3.6	2.8	1.25	.604
	Total 19.8	15.6	1.4	.62
Theft with Intent to Construct Nuclear Explosive	Suc. 30.	15	.30	.03
	No Suc. 3.2	1.9	.61	.60
	Total 33.2	17	.91	.63

*Based on group with at least one trained nuclear technologist as member and of adequate number (8 members). The expected values for groups without technical membership or adequate size are assumed to be 100-1000 times less likely for the events of theft with intent to build weapons.

**MOX fuel is assumed not to be spiked with fission products. By spiking the fuel, the expected value consequences for theft with intent to build weapons could be decreased below the values indicated for the N-yr spent fuel, as spiking would cause the MOX fuel to be as gamma active as "new" spent fuel freshly irradiated in the reactor. Such fuel would be much more difficult to handle (order of 10-100 times more difficult), and the likelihood that successful reprocessing could take place would decrease.

D.4 Comparison of Expected Value Consequences -- Open vs. Closed Cycles

The expected value consequences for open versus closed cycle alternatives are given in Table D.11. These results were derived by "folding-back" the initiation and pre-initiation event trees. Further discussion of these results is found in Chapter 6.B.

Table D.11

EXPECTED VALUE CONSEQUENCES PER FACILITY-YEAR
(In 1975 Billions of Dollars)

A. SURFF vs. Reprocessing-MOX Fabrication Facility

Event & Adversary Group Type	SURFF Facility		REP/MOX Fabrication Facility	
	with Pre*	without Pre	with Pre	without Pre
Sabotage				
Single Saboteur	3-5 x10 ⁻⁹	3-5 x10 ⁻⁶	5-10x10 ⁻⁹	5-10 x10 ⁻⁶
k=1 Armed Saboteurs	24-38x10 ⁻⁹	2.3-3.8x10 ⁻⁵	38-75x10 ⁻⁹	3.8-7.5x10 ⁻⁵
TOTAL	27-43x10 ⁻⁹	2.6-4.3x10 ⁻⁵	43-85x10 ⁻⁹	4.3-8.5x10 ⁻⁵
Single Saboteur	1.3-1.8x10 ⁻⁶	.06-.085	1.23-1.8x10 ⁻⁶	.057-.083
k=2 Armed Saboteurs	1.1-1.6x10 ⁻⁶	.009-.013	1.05-1.5x10 ⁻⁶	.009-.013
TOTAL	2.4-3.4x10 ⁻⁶	.069-.098	1.3-3.3x10 ⁻⁶	.066-.096
Nuclear Theft-Terrorism				
k=1 Many Armed Terrorists	2.1-4.2x10 ⁻⁶	.075-.15	2.1-4.2x10 ⁻⁶	.075-.15
k=2	30x10 ⁻⁹	.001	5.5x10 ⁻⁶	PuO ₂ .108 PuN .081 MOX Pellets .002 MOX Fuel .0008 TOTAL = .192
k=3	10 ⁻⁸	1.1x10 ⁻³	2.6x10 ⁻⁶	PuO ₂ .182 PuN .088 MOX Pellets .001 MOX Fuel .0005 TOTAL = .272

TOTAL: SURFF 4500-7700 \$ per facility-year REP/MOX FABRICATOR 11,500-15,600 \$ per facility year
DIFFERENCE: 7000-7900 \$ per facility year, or 160 \$ per GWe -year**

B. Transportation of N-Yr Spent Fuel vs. Fresh MOX Fuel

Event & Adversary Group Type	SURFF FACILITY		REP/MOX Fabrication Facility	
	with Pre	without Pre	with Pre	without Pre
Sabotage				
Single Saboteur	0.4x10 ⁻⁹	1.2x10 ⁻⁶	0.4x10 ⁻⁹	1.2x10 ⁻⁶
Armed Saboteurs	10.6x10 ⁻⁹	1.0x10 ⁻⁵	10.6x10 ⁻⁹	1.0x10 ⁻⁵
Nuclear Theft				
k=1	negligible	2.5x10 ⁻¹³ -5x10 ⁻¹²	negligible	2.5x10 ⁻¹³ -5x10 ⁻¹²
k=2	negligible	3x10 ⁻¹⁶	negligible	77x10 ⁻¹⁶
k=3	negligible	3x10 ⁻¹⁶	negligible	50x10 ⁻¹⁶
TOTAL	11x10 ⁻⁹	1.1x10 ⁻⁵	11x10 ⁻⁹	1.1x10 ⁻⁵

* "Pre" refers to the pre-initiation event likelihood.

** Calculated for SURFF and Reprocessing-MOX Fabrication Facility sized to handle the output of 50 1 GWe power plants per year.

Appendix E

SUPPORT CALCULATIONS FOR CHAPTER 7

E.1 Expert Opinion Concerning Nuclear Proliferation

Expert opinion concerning both the effects of nuclear proliferation on world order and the relationship of commercial nuclear power to future events of proliferation is varied and diverse. This section presents an overview of the major viewpoints expressed in the open literature regarding these topics, providing insight into current deliberations on nuclear policy.

E.1.1 Effects of Proliferation on World Order

The consequences of future events of nuclear proliferation is a much debated subject. The primary question most experts address is the relationship of nuclear proliferation to world stability; i.e., the influence of proliferation events on the likelihood of war outbreak, particularly of a nuclear variety. On a secondary level, experts (generally American) express opinions on the consequences of nuclear proliferation as they relate to the welfare of U.S. society in particular. In reviewing the vast amount of available literature on this topic¹, it became evident that three primary viewpoints exist: (i) Effects are Large and Adverse, i.e., proliferation produces large adverse effects on world order; (ii) Effects are Negligible, i.e., proliferation produces little or no effect on world order; and (iii) Effects are Beneficial, i.e., proliferation produces positive, beneficial effects on world

¹A literature search was conducted making use of the extensive bibliography prepared by Tom Graham (now at A.C.D.A.) for the Library of Congress. The bibliography lists major publications on the topic of proliferation, including books, government documents and journal articles/papers (available from Reference Research Associates, Palo Alto, Ca.).

order². Each of these viewpoints will now be expanded upon, with documentation provided.

(i) Effects are Large and Adverse

The perspective that nuclear proliferation will result in large, adverse consequences is by far the most prevalent viewpoint on the subject. Representing a quite persuasive possibility, this viewpoint prevails among many governmental decision-makers and political analysts (as is reflected in the existence of the Non-Proliferation Treaty, made effective in 1970). In essence, the thesis is advanced that further nuclear proliferation, resulting in the dissemination of nuclear weapons on a widespread level, will "jeopardize regional and global stability, increase the likelihood of nuclear war (local or general), exacerbate the threat of nuclear armed non-state terrorism, and generally complicate U.S. relations with new (potential or actual) nuclear weapons states" (p.11-12, [118]). Further, experts perceive the threat to American interests derive not so much from the mere number of Nth countries, but from the probability that proliferation will tend to be greatest in those regions with the highest potential for international conflict, e.g., the Middle East, Southern Africa, and East Asia.

Those who ascribe to this viewpoint often are experts with backgrounds in the fields of arms control and political science, who concentrate on trying to find ways to meet the objectives generally ascribed to arms control: "these objectives are taken to be primarily concerned with security: to make war, and especially nuclear war, less likely [emphasis added], and to make it less catastrophic in terms of death and destruction, if it should occur" (p. 4, [119])³. These analysts

²Only under the first viewpoint is proliferation considered specifically undesirable; it is the only perspective under which future events of proliferation are considered to imply social risk.

³This is not to insinuate that all arms control theorists and political scientists subscribe to this first viewpoint concerning proliferation effects; in fact, a significant number do not (see description of viewpoints (ii) and (iii)).

(ii) the success of internationally applied sanctions. The technical success event is in turn influenced by the number of commercial reprocessors in the NWS. The relationship between the commercial reprocessor-power reactor route to weapons material attainment vs. some eight other near-term routes was investigated in Section E.2. The success of sanctions is in turn influenced by three timing factors: (i) the time required after an Nth country is detected preparing a weapon to apply an effective sanction, (ii) the time required after detection to construct the weapon, and (iii) the time between the NWS decision and the detection of construction of a weapon². These timing considerations affect the success of sanctions based on the assumption that if sanctions are not applied "in time" (before the NWS has completed the construction of a weapon), they are unsuccessful. Conversely, if sanctions can be applied in time, they are considered successful³. The relationship between these timing state variables is shown in Fig. E.2.

For sanctions to be effective in preventing a NWS from continuing its construction efforts, the following inequality must hold:

$$t_{WUM} + t_{CON} > t_{DET} + t_{SAN}$$

That is, the detection of the construction process time added to the time it takes to apply sanctions after the detection takes place must be less than the time it takes the Nth country to acquire weapons material added to the time it takes to construct the weapon after the material is obtained. If this condition does not hold, then the NWS will have

²The NWS decision is defined to refer to the actual moment the NWS decides to acquire nuclear material for use in an atomic weapon.

³This does not take into account the very real possibility that a NWS might defy international sanctions, even if they were applied prior to the completion of the construction of a weapon, and proceed with their weapons plans.

constructed a weapon before any outside country has time enough to try to prevent it.

However, the question asked now is how does the availability of a commercial reprocessor in an Nth country influence these timing considerations? It is assumed here that the existence of such a facility has no effect on the variable t_{SAN} ; i.e., the time required to apply sanctions is independent of commercial reprocessing considerations. However, it is assumed that the existence of the commercial reprocessor-power reactor route to weapons material does influence the time between the NWS decision and detection (t_{det}) and the time required to acquire the weapons material and construct the weapon ($t_{\text{WUM}} + t_{\text{CON}}$).

Moving even further down the diagram, the number of commercial reprocessors in the NWS is influenced by the NWS response to supplier policy; if suppliers decide to restrict their export policies to NWSs, then the NWS must decide whether or not to construct its own such facility or to do without. Its decision will be influenced by the behavior of the supplier states; if the supplier states reprocess their own domestic fuel but deny NWSs access to such technology, this might influence the NWSs to build their own capacity. Finally, the non-U.S. suppliers will be influenced by the U. S. decision on domestic reprocessing; they may respond by pursuing their own programs even more vigorously because they see a technological-commercial advantage to doing so, or they may respond by following the example of the U. S. Alternatively, they may not be influenced at all by the U. S. decision, and continue their programs as planned. However, every non-U. S. supplier may not react the same way; the state variable is defined to be the aggregate response of all non-U.S. suppliers to the U. S. reprocessing decision. Finally, the U. S. reprocessing decision may influence non-U. S. supplier export policy.

The analysis procedure followed is to work backward through the diagram and calculate conditional probability relations:

$$\begin{aligned}\Delta &= \text{differential probability of proliferation between reprocessing decision options} \\ &= \{S_C|\epsilon\}_{\text{permit}} - \{S_C|\epsilon\}_{\text{delay}}\end{aligned}$$

where

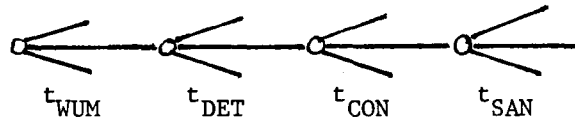
S_c = event Nth country successful at constructing weapon

$\{S_c|\epsilon\}_i$ = probability proliferation event S_c occurs as a function of reprocessing decision option i

But this likelihood is conditional upon the success of sanctions (S_s) and the technical success of a NWS in weapon construction (T_s):

$$\{S_c|\epsilon\}_i = \{S_c|\bar{S}_s, T_s|\epsilon\} \cdot \{\bar{S}_s|\epsilon\} \cdot \{T_s|\epsilon\}$$

where \bar{S}_s is the event sanctions are not successful; $\{\bar{S}_s|\epsilon\} = 1 - \{S_s|\epsilon\}$. Then, $\{S_s|\epsilon\}$ can be estimated by discretizing assigned priors on the timing state variables.



In this event tree, 81 possible states-of-the-world with regard to the critical timing consideration defined earlier are described. Then an estimate for $\{S_s|\epsilon\}$ is obtained from the ratio of the number of these states that satisfy the inequality $t_{WUM} + t_{CON} > t_{DET} + t_{SAN}$ divided by the total number of defined possible states (81).

The priors on two of these timing considerations are influenced by whether or not a NWS has a commercial reprocessor operating. Thus, estimates for $\{S_s|\epsilon\}$ can be obtained for two cases: (i) a NWS has a commercial reprocessor (N_R), and (ii) a NWS does not have a commercial reprocessor (\bar{N}_R). Then the likelihood of these events is estimated as a function of reprocessing decision option.

Finally, a new estimate for Δ based on this sampling procedure and the estimate on the technical success likelihood is obtained:

$$\Delta = [\{\bar{S}_s|\epsilon\}_{\text{permit}} \cdot \{T_s|\epsilon\}_{\text{permit}} - \{\bar{S}_s|\epsilon\}_{\text{delay}} \cdot \{T_s|\epsilon\}_{\text{delay}}]$$

where $\{T_s|\epsilon\}_{\text{permit}} = [\{T_s|\epsilon\}_{\text{rel}} + .03]$ (from assessment of relative attractiveness, E.2]. Then

$$\begin{aligned} \Delta &= [(\{\bar{S}_s|\epsilon\}_{\text{Permit}} \cdot [\{T_s|\epsilon\}_{\text{Delay}} + .03] - \{\bar{S}_s|\epsilon\}_{\text{Delay}} \cdot \{T_s|\epsilon\}_{\text{Delay}})] \\ &= [(.03 \cdot \{\bar{S}_s|\epsilon\}_{\text{Permit}}) + \{T_s|\epsilon\}_{\text{Delay}} (\{\bar{S}_s|\epsilon\}_{\text{Permit}} - \{\bar{S}_s|\epsilon\}_{\text{Delay}})] \end{aligned}$$

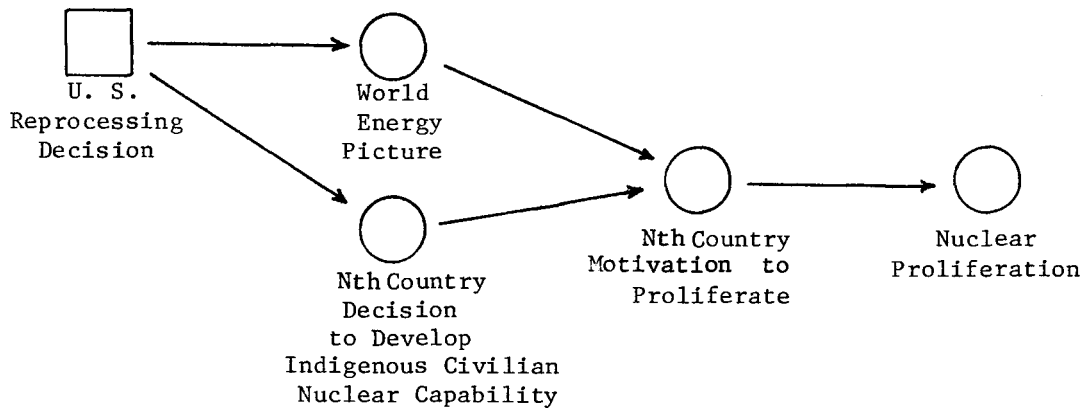
E.4 Modeling Motivational Factors

As was discussed in Section E.3, the differential likelihood of proliferation (Δ) between reprocessing decision options includes a probability term reflecting motivational factors prompting the Nth country to make a positive decision to acquire weapons: $\{P_{MOT}|R_{DEC} \epsilon\}$. It can be argued that this likelihood is independent of (is not influenced by) the U. S. reprocessing decision (R_{DEC}); i.e.,

$$\{P_{MOT}|R_{DEC} \epsilon\} = \{P_{MOT}|\epsilon\}$$

In that case, Δ is assumed solely conditional upon the events shown in the influence diagram (Figure E.1).

However, there are those experts that argue that the U. S. reprocessing decision does influence Nth country motivational factors (see E.1.2, part (iii)). These experts contend that motivational factors are influenced by two separate events that are in turn influenced by the U. S. reprocessing option chosen. This relationship can be placed into influence diagram format:



To these experts, the world energy picture greatly influences Nth country motives to proliferate, since energy scarcity could create greater stress in those regions already identified as future proliferant zones. Moreover, the U. S. reprocessing decision may influence the Nth country decision to develop its own civilian nuclear capabilities, deciding to rely on its own domestic capabilities rather than on foreign suppliers. For

these experts, the effect of motivational factors would be to further reduce Δ , or to actually cause Δ to go negative; i.e., the likelihood of proliferation becomes greater if reprocessing is delayed or prohibited. However, there are a multitude of other motivational factors that influence the Nth country decision to proliferate.

One way to model such factors is to consider the Nth country as a rational decision-maker, where a rational decision to acquire weapons capability is influenced by the magnitude of the net benefits the Nth country perceives it can attain through such an endeavor. The net benefits are defined to be equivalent to the difference between benefits and costs associated with the endeavor, which can be classified into two succinct categories: (i) economic, and (ii) non-economic. Economic cost-benefits are those that can be easily measured in dollar terms; non-economic are those that are not easily measured in dollar terms -- are less tangible consequences not directly controlled by economic conditions. Under the economic category of cost-benefits related to nuclear weapons status are:

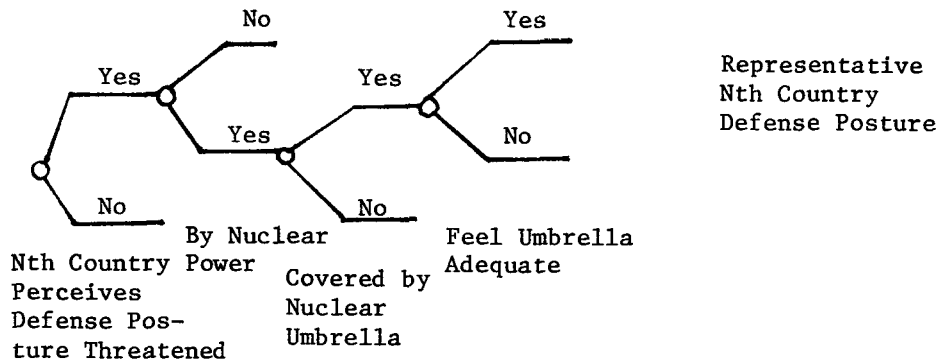
- | | |
|---|--|
| (i) the economic cost to the Nth country of constructing facilities and financing weapons production/delivery capability. | (ii) potential change in world economic status as a result of weapons development (through concessions, change in power, etc.) |
|---|--|

Under the potential change in world economic status are the following:

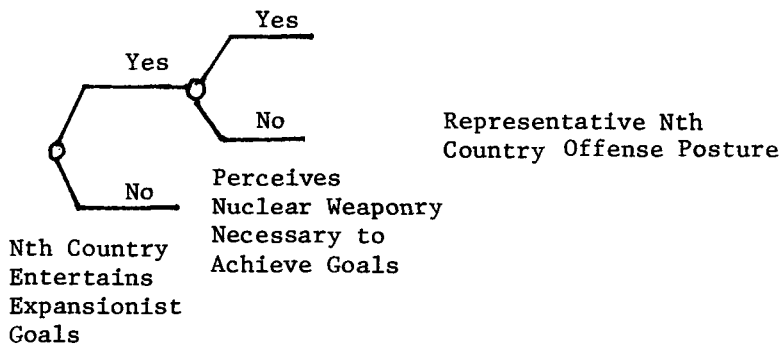
- (i) change in wealth (GNP/year), and
- (ii) change in economic security, as reflected in ownership of resources and businesses, status of imports/exports (guaranteed markets), etc.

If Category (ii) is perceived to outweigh in benefits, the economic costs of Category (i), then the Nth country would be encouraged to take steps to develop a weapons system. However, non-economic considerations also need to be factored into the decision. Under the non-economic category are:

- (i) Defense posture of the Nth Country: Perceives that its position is threatened by a regional member, and the regional member is a nuclear (or non-nuclear) state; i.e., the Nth country perceives that its military capability is insufficient for defense purposes, reflecting whether or not a threatening regional member is a nuclear or non-nuclear state and whether or not the Nth country is covered under a defense umbrella that it perceives to be adequate. These factors can be related as follows:



- (ii) Offense posture of Nth country: Perceives that it must be prepared to attack regional neighbors to further its (1) expansionist goals, or (2) other goals (change in world status), and feels that nuclear weapons are required for such goals. In the case of an aggressive, warlike country, it may perceive that its expansionist goals are beneficial, and can be attained with a high probability of success by acquiring nuclear weapons. In this case, the country is likely to proliferate regardless of other considerations.



Given a careful assessment of these factors, in particular on a country-by-country basis, it may be possible to better estimate the likelihood that an Nth country's motivations for developing nuclear weaponry are affected by the U.S. decision on reprocessing. However, these studies are beyond the scope of the present work; this section is included only to provide ideas on how such future studies might approach the problem of modeling Nth country motivational factors.