NUREG/CR-3929
ANL/AA-29

Loss-of-Benefits Analysis for Nuclear Power Plant Shutdowns: Methodology and Illustrative Case Study

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ARGONNE NATIONAL LABORATORY
Energy and Environmental Systems Division

prepared for

U. S. NUCLEAR REGULATORY COMMISSION

under Interagency Agreement DOE 40-550-75

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NUREG/CR-3929
ANL/AA-29
(Distribution
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LOSS-OF-BENEFITS ANALYSIS FOR NUCLEAR POWER PLANT SHUTDOWNS: METHODOLOGY AND ILLUSTRATIVE CASE STUDY

by

J.P. Peerenboom, W.A. Buehring, and K.A. Guziel

Energy and Environmental Systems Division
Integrated Assessments and Policy Evaluation Group

November 1983

work sponsored by

U.S. NUCLEAR REGULATORY COMMISSION
Office of Nuclear Regulatory Research
Washington, D.C. 20555

NRC FIN No. A2223

ABSTRACT

A framework for loss-of-benefits analysis and a taxonomy for identifying and categorizing the effects of nuclear power plant shutdowns or accidents are presented. The framework consists of three fundamental steps: (1) characterizing the shutdown; (2) identifying benefits lost as a result of the shutdown; and (3) quantifying effects. A decision analysis approach to regulatory decision making is presented that explicitly considers the loss of benefits. A case study of a hypothetical reactor shutdown illustrates one key loss of benefits: net replacement energy costs (i.e., change in production costs). Sensitivity studies investigate the responsiveness of case study results to changes in nuclear capacity factor, load growth, fuel price escalation, and discount rate. The effects of multiple reactor shutdowns on production costs are also described.

NRC FIN No. A2223
NRC FIN Title: Loss-of-Benefits Estimation for Nuclear Plant Outages

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ACKNOWLEDGMENTS

The authors wish to extend their appreciation to several persons who made key contributions to this study. Jack VanKuiken provided guidance in developing the case study, running the production-cost model, and interpreting the results. In addition, P.K. Niyogi (project officer) and Sidney Feld of the Nuclear Regulatory Commission, Eugene Oatman of the Electric Power Research Institute, and David Strip of Sandia National Laboratories prepared reviews that were helpful in articulating the ideas described in this report. Finally, the authors thank the following individuals for their contributions to this report: Donna Kenski, editor; Shawne Gilstrap, secretary; Barbara Salbego and Shirley Biocic, word processing operators.

SUMMARY

To be defensible, regulatory decisions about nuclear power plants must be based on comprehensive analyses of both the risks of reactor operation and the consequences of regulatory actions taken to reduce those risks. Regulatory actions that result in reactor shutdowns or licensing delays, for example, may have consequences such as costs of replacement energy and capacity, costs of reduced system reliability, environmental and socioeconomic impacts, and increased public risks from the use of replacement fuels such as coal. Such consequences, or losses of benefits, may or may not be important compared to the risks of operation in any particular case. However, the consequences of nuclear power unavailability must be determined to demonstrate explicitly the risk-benefit tradeoffs inherent in any decisions involving power plant licensing or operation.

This report categorizes and describes the wide range of effects associated with regulation- or accident-induced nuclear plant shutdowns. It analyzes selected effects for a case study of a hypothetical nuclear plant shutdown. A generalized framework for loss-of-benefits analysis (Fig. S.1) and a loss-of-benefits taxonomy are presented. The framework consists of three fundamental steps: (1) characterizing the shutdown, which involves defining the cause of the shutdown, the expected duration of the outage, and the mitigation measures that may be applicable; (2) identifying relevant loss-of-benefits considerations, which involves screening all possible effects of reactor shutdowns and determining which are applicable; and (3) quantifying effects. The taxonomy is used to facilitate step 2. A decision analysis approach for integrating loss-of-benefits considerations into the regulatory decision process is also outlined.

The case study examines the loss of benefits that would result from a hypothetical long-term shutdown (1984-1993) of the Fitzpatrick Nuclear Station in Scriba, New York. This illustrative case study focuses on effects on the New York Power Pool. Specifically, it addresses (1) net replacement energy costs and generating system reliability, which were calculated using a production-cost model developed at Argonne, and (2) net risks of using replacement fuel. A series of sensitivity studies examines the responsiveness of production-cost results to changes in key parameters and assumptions. The effects of multiple reactor outages, changes in nuclear capacity factors, changes in load growth, fuel price escalation, and alternative discount rates are investigated.

Case study results show that significant increases in production costs (up to \$117 million per year in the early years of a long-term shutdown) could be expected if Fitzpatrick is shut down. On a per-megawatt-year basis, the cost increase due to the shutdown varies from about \$0.12-\$0.14 million. The production-cost increases exhibit a seasonal dependence, subject to maintenance schedules and peak load variations.

Reliability is not an important issue in this case study; the average generating reserves for the New York Power Pool (based on Argonne's representation) are about 48% with Fitzpatrick operating (1984), and about 44% without the 810-MW Fitzpatrick unit. The pool's average planning requirement is 22%. However, multiple reactor outages could lead to long-term reliability problems. In many other regions of the country, reliability is a more critical issue for single-reactor shutdowns.

Most replacement energy (about 80% in 1984 and 60% in 1993) for the shutdown case is generated by expensive oil-fired generating units. High-sulfur coal units supply only 7% of the replacement generation in 1984. However, because the power pool's oil-displacement policies are aggressive, these units generate over 17% of the replacement kilowatt-hours in 1993. Firm and economy power purchases are maintained at a fairly constant level (about 18×10^9 kWh/yr) over the 10-year study period.

Sensitivity analysis shows that assumptions about load growth, capacity factors, fuel prices, fuel price escalation rates, and the discount rate can all significantly affect the production-cost results. For example, if the assumed rate of load growth increases from the reference value of 1.7%/yr to 3%/yr, the annual production-cost increase for the Fitzpatrick shutdown grows by over 10% by the end of the study period. Changing Fitzpatrick's capacity factor from the reference value of 57% to a more optimistic value such as 70% increases production costs by $154 million, as opposed to the $117 million production-cost increase in the reference case.

LOSS-OF-BENEFITS ANALYSIS FOR NUCLEAR POWER PLANT SHUTDOWNS: METHODOLOGY AND ILLUSTRATIVE CASE STUDY

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1 INTRODUCTION

1.1 BACKGROUND

Concerns about the risks of nuclear power plant operation and efforts to quantify those risks have intensified in recent years, particularly since the accident at Three Mile Island. Coupled with this increased attention to reactor safety has been an awareness that reactor outages, whether they are caused by accidents or forced by new regulations, produce significant negative effects on consumers.

These effects, collectively called loss of benefits, include replacement energy and capacity costs, costs associated with reduced system reliability, a wide range of possible environmental and socioeconomic impacts, and increased public risks due to the use of alternative replacement fuels such as coal.[1]

The loss of benefits is an important consideration in regulatory decision making. Subject to minimum safety standards, regulatory decision making basically involves balancing the risks of reactor operation against the loss of benefits that would result from regulatory actions taken to reduce those risks. The extensive testimony presented before the Atomic Safety and Licensing Board on the system reliability, economic, environmental, and socioeconomic consequences of closing the Indian Point reactors clearly illustrates both the importance and controversial nature of loss-of-benefits considerations.[2-4]

Previous studies have shown that production costs increase significantly whenever an operating nuclear power plant is shut down, whether the shutdown is due to a regulatory action or a reactor accident.[1,5] The change in a utility system's production costs represents the change in the variable costs incurred to produce electricity. These variable costs include fuel costs, purchased energy costs, and variable operation and maintenance (O&M) costs. Because the most economic units in a utility system operate at near-capacity levels (to the extent possible given various operating constraints), the cost of replacement energy, either for fuel used directly by the utility or for energy purchases from interconnected utilities, is usually higher than the generation cost of the affected nuclear unit.

Nuclear reactor outages can also have other wide-ranging financial effects on a utility company and its customers. For example, the affected utility will incur unrecovered capital costs for reactors that are permanently shut down, interest costs, increased inventory costs for replacement fuels, earlier-than-expected decommissioning costs for permanent shutdowns, replacement capacity costs, and other fixed costs.

Unlike production costs, however, which depend only on the type of generating units in the power system, these potential economic effects also depend on the type of operating utility, its financial structure, previous plant investment decisions, and state and federal regulations governing electric utility financial practices.

Another important point to consider when examining a nuclear outage is that reactor shutdowns can directly affect human health and safety. For instance, the increased reliance on fossil fuels, such as coal, to supply replacement energy can substantially increase systemwide human health and safety impacts. Coal mining, transport, and conversion operations all tend to increase health and safety risks. The importance of these risks compared to the risks of continued plant operation must be determined on a case-by-case basis. Regional and global problems such as increasing acid deposition and atmospheric carbon dioxide levels have also been associated with fossil fuel use. These problems are currently the focus of considerable national and international debate.

Clearly, defensible regulatory decisions require comprehensive analyses of both the risks of reactor operation and the loss of benefits that would result from a reactor outage necessitated by the regulatory action under consideration. This concept is illustrated in Fig. 1.1, which shows a framework for analyzing alternative regulatory actions of the U.S. Nuclear Regulatory Commission (NRC). For each action being considered, the loss of benefits that would result from the unavailability of a particular

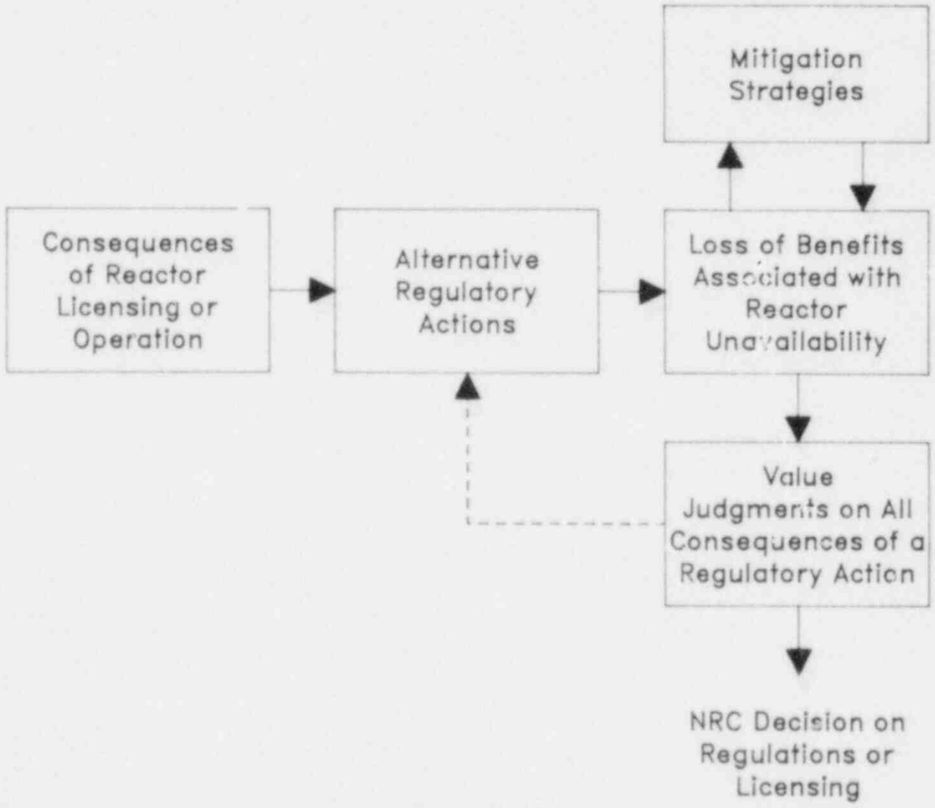

FIGURE 1.1 Framework for NRC Analysis of Alternative Regulatory Actions

nuclear unit must be evaluated. This evaluation must be coupled with an analysis of the affected utility's options for mitigating the effects of the regulatory action. For example, temporarily postponing scheduled maintenance, purchasing emergency energy, or adding new generating capacity may be options in specific cases. Finally, after data on the benefits and risks are available, the tradeoffs between the alternate actions and their consequences must be judged. In some cases, these judgments may indicate a need to examine other alternatives; this possibility is shown by the feedback in Fig. 1.1. The analysis results in a regulatory or licensing decision that is based on an explicit consideration of the actual risk-benefit tradeoffs.

1.2 OBJECTIVES AND APPROACH

This report categorizes and describes the wide range of effects (loss of benefits) that are associated with shutdowns of nuclear power plants, and it analyzes selected effects for a case study of a hypothetical nuclear plant shutdown. Specifically, the objectives of this study are to:

1. Identify and characterize the loss of benefits that results from nuclear power plant outages,
2. Demonstrate the capabilities of a production-cost model and supporting data base that have been developed to aid in the economic evaluation of both short- and long-term reactor outages,
3. Estimate and describe the changes in production costs, reliability, and fuel use that would result from the long-term shutdown of a currently operating nuclear power plant,
4. Estimate and describe the changes in production costs, reliability, and fuel use that would result from multiple reactor shutdowns,
5. Identify and discuss the risks of using replacement fuels for a long-term nuclear plant shutdown, and
6. Identify key assumptions and parameters used in the analysis, and perform sensitivity studies to investigate the responsiveness of results to changes in those assumptions and parameters.

The case study and sensitivity analyses defined in the last four objectives have a twofold purpose: to (1) illustrate several of the important loss-of-benefits considerations identified in objective 1 and (2) demonstrate the production-cost model and data base identified in objective 2.

The loss-of-benefits research described in this report was performed by Argonne National Laboratory and sponsored by the Nuclear Regulatory Commission's Office of Nuclear Regulatory Research. This research focused on developing and applying techniques for estimating replacement energy costs that would result from reactor shutdowns forced by regulations or accidents. As part of this effort, a general framework for loss-of-benefits analysis was developed and a wide range of impacts in addition to replacement energy costs was identified. However, quantifying all of the identified impacts is beyond the scope of this effort.

The case study of a single-reactor shutdown characterizes the loss of benefits that would result from a hypothetical 10-year outage (1984-1993) of the Fitzpatrick nuclear power station.* This 810-MWe boiling-water reactor, built in the early 1970s, is located in north-central New York State and is owned and operated by the Power Authority of the State of New York (PASNY), one of the members of the New York Power Pool. The production-cost, fuel use, and reliability results presented in this report for a Fitzpatrick shutdown are based on probabilistic simulations of the entire New York Power Pool as opposed to simulations of PASNY alone. This approach was taken because power pool simulations provide a more realistic estimate of shutdown impacts, especially for centrally dispatched pools or other pooled utilities, such as PASNY, that have extensive transmission interties.

However, the economic effects of a reactor shutdown when measured on the individual utility level can still be significantly greater than the economic effects measured for the power pool as a whole. For example, in the case of the hypothetical shutdown of Fitzpatrick, PASNY customers may face a large increase in generating cost (measured in cents per kilowatt-hour) to pay for the increased purchases from other members of the pool. However, by viewing the net effects of the shutdown from the power pool perspective, most of the expected replacement generation can be specifically identified with individual generating units in the pool and transfer payments between utilities can be eliminated.** This approach is more meaningful for NRC policy decisions because it provides a truer picture of the net cost from a societal perspective.

The probabilistic simulations for the case study and sensitivity analyses were performed with a production-cost and reliability model called ICARUS (Investigation of Costs and Reliability in Utility Systems). This model, which was developed at Argonne, efficiently simulates large utilities, power pools, and reliability council regions.[6] The procedures used in ICARUS significantly reduce the computational restrictions imposed by conventional simulation methods, and make it possible to simulate the many generating units typically associated with a power pool or region.

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*The selection of this particular reactor and power pool for the illustrative case study does not in any way signify that this reactor has a greater likelihood than any other U.S. reactor of being affected by a shutdown order. The model and data base used to perform the production-cost analyses for this case study are being used by Argonne National Laboratory to perform similar analyses for all operating and planned reactors in the United States.

**For example, suppose Utility A sells electricity to Utility B for the cost of generating the electricity plus 50% of the amount Utility B saves by purchasing electricity instead of generating it. The extra 50% is, in effect, a transfer payment from customers of Utility B to customers of Utility A. Such transfer payments, while potentially important at the individual utility level, can be neglected in power pool calculations.

An extensive data base of electrical utility systems coupled with a highly flexible data assembly package, called ADAP, has also been developed at Argonne to accurately provide the system representations (i.e., compositions of the generating systems) required for simulation.[7] The data base contains a detailed inventory of generating units in the United States (with appropriate utility and power pool designations) and a file of operating characteristics and cost parameters for the different types of facilities represented in the data base.

The composition of the generating system (or pool) under study and the performance characteristics of units in that system are extremely important parameters in any production-cost analysis. A representation of the New York Power Pool was constructed with ADAP and used in the ICARUS simulations to calculate unit energy assignments, unit fuel consumption, system reliability, and costs of system operation for the case study.*

The case study compared the results of two separate simulations (Fig. 1.2): (1) a case in which all units, including the reactor of interest, are assumed to operate normally and (2) a case in which the designated reactor is assumed to be unavailable for generation. To provide a consistent basis for comparison, a uniform set of assumptions

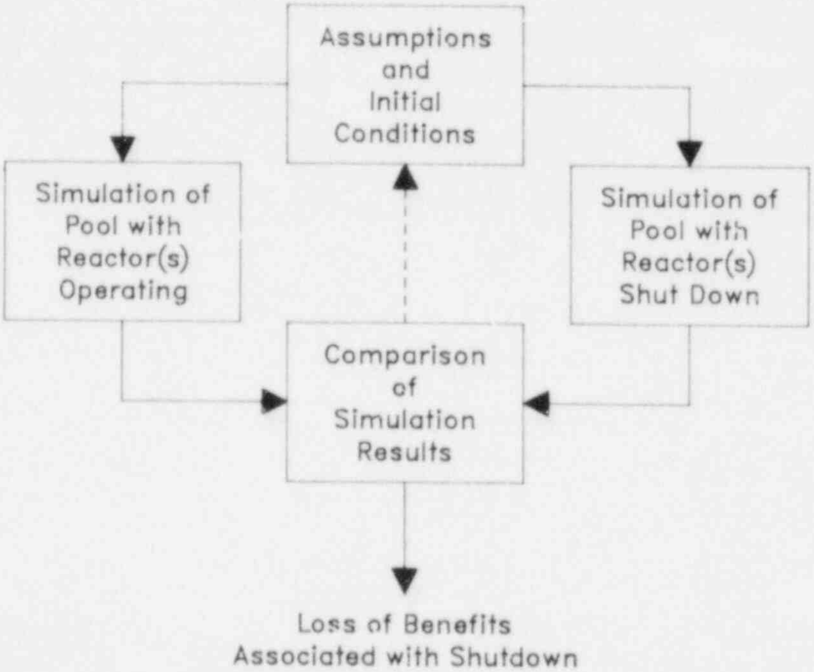

FIGURE 1.2 Simplified Representation of Procedure for Quantifying Loss-of-Benefits Effects

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*Since the completion of this study, ADAP has been updated to represent systems more accurately. Although some data for the New York Power Pool have been refined, the results presented here would not be significantly affected by the new data.

was developed and used in both cases. This consistency is important because results are not meaningful unless identical assumptions (e.g., load growth, cost escalation factors, fuel prices, and expansion plans) are used in both cases. The maintenance schedules for all units in the power pool (except the designated reactor) were kept the same in both cases. Net changes in power pool operations and costs were estimated by directly comparing the results of the two cases. Although the simulations covered a 10-year period, mitigation strategies, such as the addition of replacement capacity or changes in existing capacity expansion plans, were not investigated.

1.3 ORGANIZATION

Section 2 presents and discusses a general framework for loss-of-benefits analysis and a taxonomy of loss-of-benefits considerations. The taxonomy identifies the economic as well as the noneconomic consequences of reactor outages. This section also presents a decision analysis approach to regulatory decision making that explicitly includes loss-of-benefits considerations. Section 3 identifies the assumptions used in the loss-of-benefits case study and gives some background on the New York Power Pool. The case study demonstrates the capabilities of the production-cost model ICARUS and the data base and data assembly package ADAP. Section 4 presents and discusses the case study results for the Fitzpatrick shutdown. Section 5 examines the results of various sensitivity studies that investigate how changes in key variables affect the base case loss-of-benefits results (described in Sec. 4). Included in this section are sensitivity studies examining the effects of changes in load growth, nuclear plant capacity factors, fuel price escalation rates, and the level of capacity shut down (i.e., multiple-unit shutdowns). The final section presents a number of conclusions and observations about loss-of-benefits analysis.

2 LOSS-OF-BENEFITS METHODOLOGY

This section presents a general framework for loss-of-benefits analysis and a taxonomy for identifying and categorizing the effects that could result from nuclear plant shutdowns. Methods for estimating a number of loss-of-benefits effects are identified. A decision analysis approach for integrating loss-of-benefits considerations into the regulatory decision process is also outlined.

2.1 FRAMEWORK FOR LOSS-OF-BENEFITS ANALYSIS

Loss-of-benefits analysis for nuclear plant shutdowns involves three fundamental steps (Fig. 2.1):*

1. Characterizing the shutdown,

2. Identifying relevant loss-of-benefits considerations, and

3. Quantifying effects.

Characterizing the shutdown (step 1) entails defining the cause of the shutdown (i.e., an accident or regulatory action), the expected duration of the outage, and any options available to the affected utility and power pool to mitigate the effects of the outage. For example, an order for immediate shutdown would allow few options for mitigation. However, if a utility receives warning that a forthcoming regulatory action will necessitate a reactor shutdown, it can take short-term mitigation measures, such as changing the scheduled maintenance of generating units throughout the power pool. If shutdown flexibility is allowed, a utility could possibly complete some safety modifications during regularly scheduled reactor maintenance. In contrast, very lengthy or permanent shutdowns may lead to a complete reoptimization of capacity retirement and expansion plans. The expected duration of an outage [e.g., short-term (<1 yr), long-term (≥1 yr), or permanent] is clearly an important factor in deciding what mitigation options are feasible. Potential utility responses to reactor outages (i.e., mitigation options) are discussed in Ref. 1.

Identifying relevant loss-of-benefits considerations (step 2) involves screening all possible effects of reactor shutdowns and, on the basis of the shutdown characterization, determining the applicability of each. A taxonomy of loss-of-benefits considerations is presented in Sec. 2.2 to facilitate this step in the analysis. The cause and duration of an outage are two key factors in defining the required scope of analysis.

Quantifying the relevant loss-of-benefits effects (step 3) identified in step 2 can be extremely difficult due to uncertainties, extensive data requirements, time

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*This framework is also applicable to loss-of-benefits analyses of reactor deratings and licensing delays.

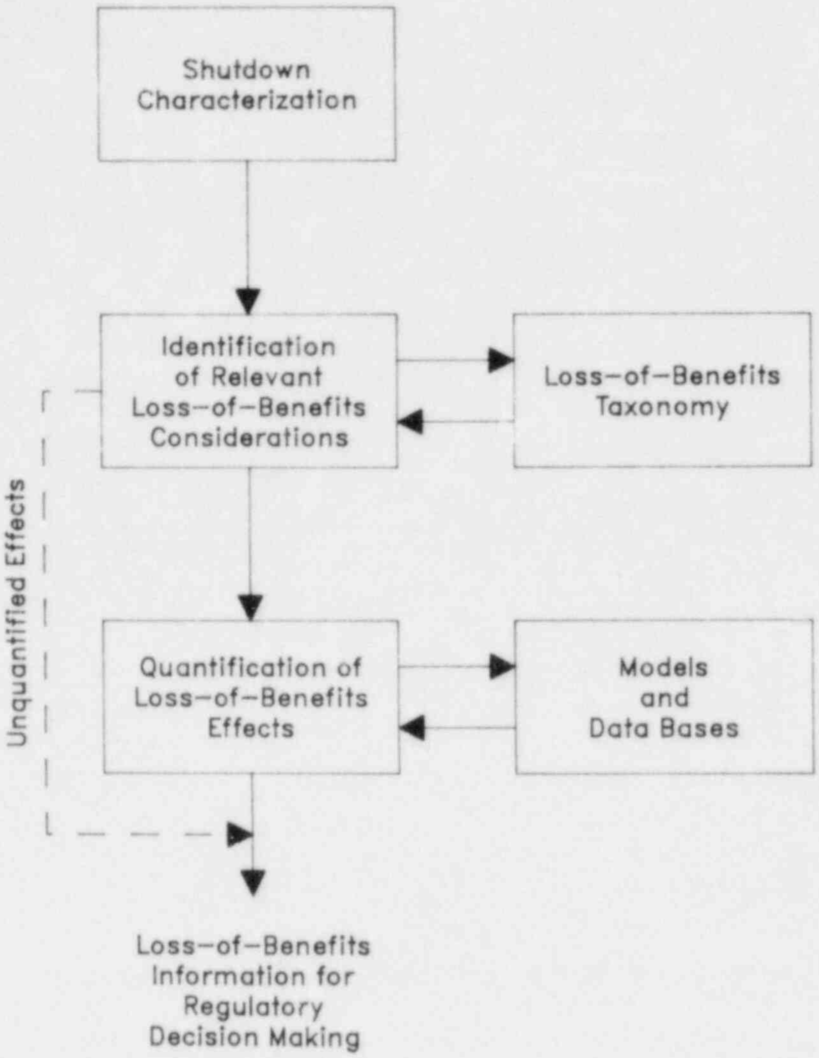

FIGURE 2.1 Framework for Loss-of-Benefits Analysis

constraints, or a lack of appropriate models. For example, detailed production-cost and reliability models are typically required to analyze replacement energy costs, while financial models are usually required to fully analyze the impacts of a reactor shutdown on the utility and its customers. For permanent shutdowns, capacity expansion models and detailed engineering cost models may also be employed to reoptimize the power pool's long-range capacity expansion plans. Finally, different types of health-impact and consequence models may be used to analyze the risks of replacement fuel use and reactor accidents.

The models developed to make these calculations are usually data-intensive and require broad assumptions about the reactor under consideration, its surrounding environment, and the affected utility and power pool. The need for such detailed models depends on the particular reactor shutdown under consideration. In some cases, such as for minor safety modifications that can be completed during regularly scheduled maintenance, relatively simple models or "back-of-the-envelope" calculations may be sufficient. For more-complex problems, detailed analyses involving the use of many models may be necessary.

A simplified representation of the procedure for quantifying loss-of-benefits effects was presented in Fig. 1.2. Two simulations are typically required: one based on normal reactor operation and the other based on the shutdown characteristics identified in step 1. In some instances, however, such as when capacity expansion plans are reoptimized, the existing utility and power pool expansion plans may serve as a basis for comparison.

Some of the important loss-of-benefits considerations identified in step 2 may be difficult to quantify (e.g., psychological stress). Nevertheless, this information must be made available, along with the quantified loss-of-benefits information, to the appropriate decision makers.

The importance of the loss-of-benefits effects quantified in step 3 and other recognized but unquantified reactor shutdown effects in comparison to the risks of continued reactor operation depends on individual risk attitudes and value judgments. Section 2.3 describes a decision analysis approach for explicitly incorporating risk attitudes and value judgments in the regulatory decision process.

2.2 LOSS-OF-BENEFITS TAXONOMY

In broad terms, the loss of benefits associated with a nuclear power plant outage refers to the outage's effects on a utility company (or power pool) and its customers. These effects can be directly or indirectly attributable to the outage and include both economic and noneconomic impacts. Theoretically, any perturbation from normal operation of a utility or power pool that is caused by an accident- or regulation-induced outage of an operating reactor should be considered in a loss-of-benefits analysis. These perturbations include systemwide effects (e.g., fuel cycle impacts) that occur outside the utility or power pool service territory. The importance of any particular effect, of course, depends on many factors, including the generating characteristics of the affected utility and power pool, the severity and duration of the outage, the type and cost of replacement fuels, and the existing generating-capacity reserve in the pool.

For identification and classification, loss-of-benefits considerations can be divided into two broad categories (as shown in Fig. 2.2): economic impacts and noneconomic impacts. Economic impacts fall into three main subcategories: net replacement energy costs (i.e., the net costs of generating or purchasing energy to replace the lost nuclear generation);* financial considerations (i.e., economic impacts other than net replacement energy costs and accident-related costs); and (if applicable) the costs specifically associated with a reactor accident. In the case of a reactor accident, both net replacement energy costs and financial considerations must be

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*A number of the subcategories are measured in "net" terms; that is, the consequences when the nuclear unit of interest is operating normally are subtracted from the consequences when that unit is shut down.

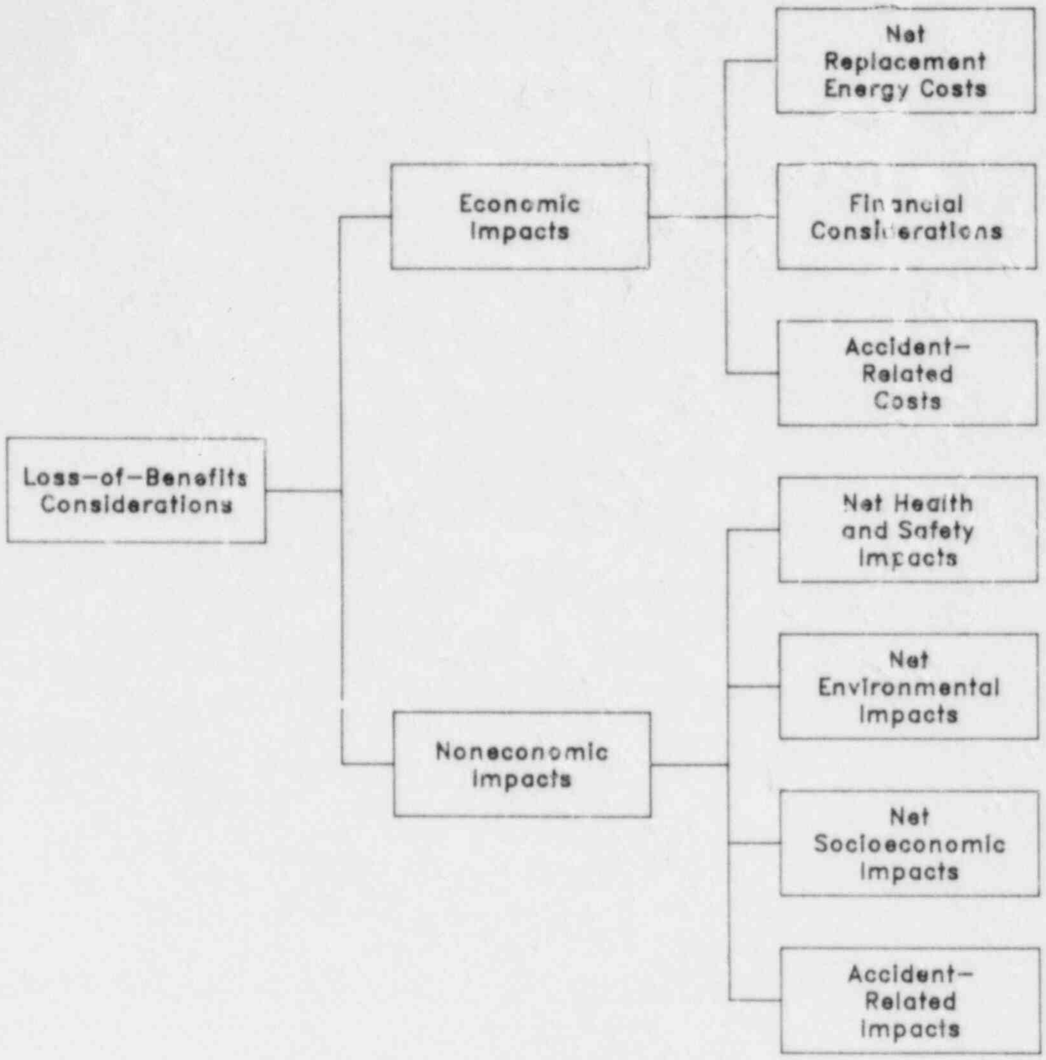

FIGURE 2.2 Breakdown of Loss-of-Benefits Considerations

examined. Noneconomic impacts fall into four broad subcategories: net health and safety impacts, net environmental impacts, net socioeconomic impacts, and accident-related impacts.

The wide variety of impacts in the seven subcategories identified in Fig. 2.2 could contribute significantly to the overall loss of benefits associated with a particular reactor outage. Each subcategory of loss-of-benefits effects is briefly described in this section; as noted in Sec. 1, only one subcategory, net replacement energy costs, is examined in detail in this report.

2.2.1 Net Costs of Replacement Energy

One of the most direct consequences of a reactor outage is the increase in a utility system's production costs. The production-cost increase reflects the change in the variable costs incurred to produce electricity. These variable costs include replacement fuel costs; shutdown-caused purchased energy costs; nonnuclear, variable O&M costs that may change throughout the generating system; avoided nuclear fuel costs; and avoided nuclear variable O&M costs. As Fig. 2.3 shows, unserved energy costs can also be included in this category.

Costs of electrical shortages, including costs incurred by customers over outages of varying duration, have been examined in a number of recent studies.[8-11] Typical estimates for the value of unserved energy fall in the range $0.1-1.0/kWh, and in some cases these costs constitute a substantial fraction of the total cost of replacement energy.[1] A detailed guide for reviewing estimates of production-cost increases that result from nuclear plant outages has been developed by Argonne for the Nuclear Regulatory Commission.[5] The production-cost and reliability model, ICARUS, and data base and data assembly package, ADAP, are designed to calculate net replacement energy costs.

2.2.2 Financial Considerations

Many economic impacts other than net costs of replacement energy and costs specifically related to accidents can result from a reactor outage. These impacts have

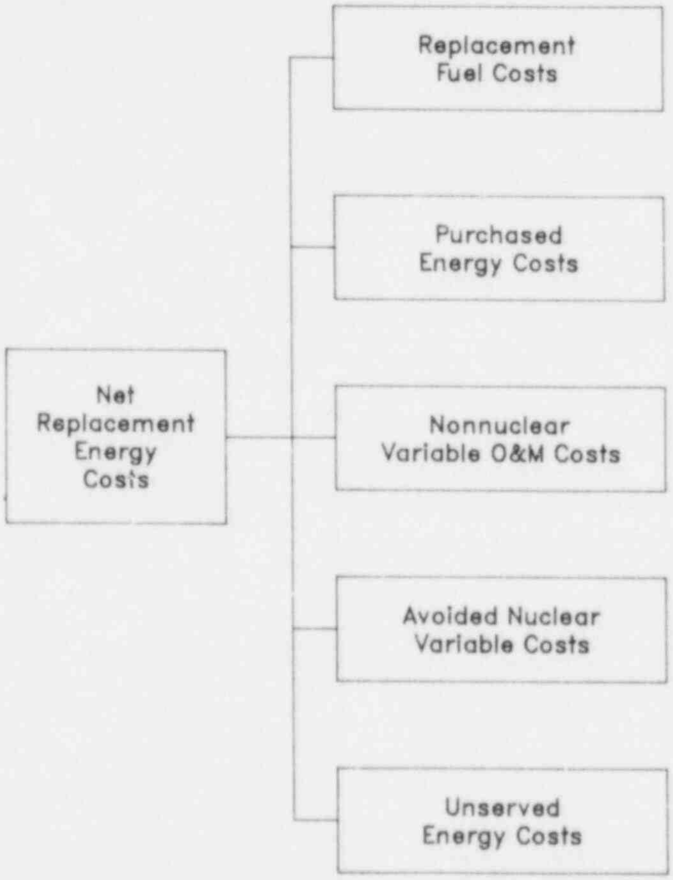

FIGURE 2.3 Breakdown of Net Replacement Energy Costs

been grouped under the category of financial considerations. As Fig. 2.4 illustrates, the permanence of the outage being evaluated is an important consideration in characterizing these impacts.

Costs of permanent reactor shutdowns fall into four categories:

- Costs of unrecovered capital investment in the plant, equipment, and fuel, which may have to be recovered in alternative ways;
- Premature decommissioning costs, that is, decommissioning costs that occur earlier than expected;
- Premature fuel storage and disposal costs; and
- Costs of major repairs that would be avoided if the reactor is shut down.* (These avoided costs can be considered a benefit of shutting the reactor down.)

These considerations may or may not be significant, depending on factors such as the reactor's age when shut down; state and federal regulations about the recovery of capital investments under premature shutdown conditions; and methods used to accumulate funds for decommissioning, fuel storage, and fuel disposal. If a permanent shutdown is ordered early in a reactor's expected operating life, for example, substantial plant investment costs (both sunk capital and carrying charges) must be recovered. Because these costs are typically recovered over the book life (which may differ from the actual operating life) of the reactor, an alternative means of retiring this debt is necessary. Tax write-off schedules must also be modified. Whether rate payers or stockholders are liable for these unrecovered costs must be determined on the basis of the particular circumstances surrounding the shutdown. If a mills/kilowatt-hour charge is used to establish a decommissioning fund, the fund will obviously be inadequate to cover such costs for early shutdown cases. One potential complication in this evaluation is that decommissioning costs could be greater for older, more irradiated, nuclear power plants.

The second category of financial considerations applies to both permanent and temporary shutdowns. The eight types of costs listed in Fig. 2.4 must be reviewed on a case-by-case basis to determine their applicability. The fixed O&M cost for a nuclear power plant that is permanently shut down may remain constant for the first year or two after an outage, but will likely decrease over time during a long-term outage. For very lengthy or permanent shutdowns, this cost may drop essentially to zero after a few years, thus becoming an avoided cost. Stockpiling replacement fuels such as coal and oil can lead to a variety of fuel inventory costs. If a utility decides to build replacement capacity as a result of a long-term or permanent reactor shutdown, it will incur substantial capital investment, planning, and other costs. Alternatively, if a utility

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*Only those costs that are beyond what would have accrued had the plant continued to operate as planned must be considered. Thus, the effects of alternative cost recovery schemes must be evaluated and compared to base case operation.

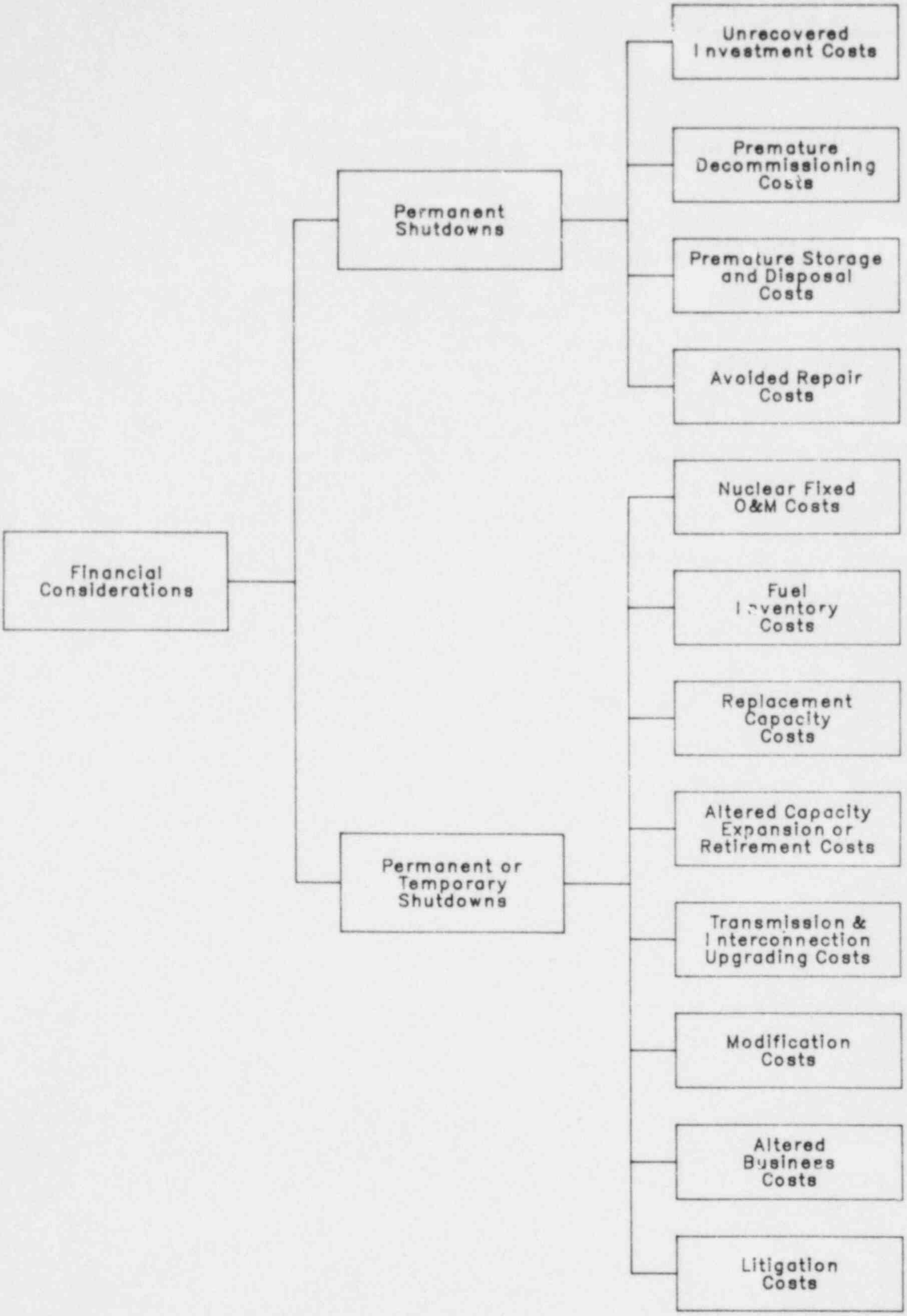

FIGURE 2.4 Breakdown of Financial Considerations

alters its capacity expansion plan by either advancing the start-up of a new generating unit or deferring the retirement of an older generating unit, it may incur substantial cost penalties. Another possible course of action in response to a shutdown would be to improve transmission and interconnection capabilities with neighboring utilities. The costs of such decisions must be included (if applicable) in comprehensive loss-of-benefits analyses.

If a reactor is shut down for safety-related modifications, the costs of those modifications must also be considered in the analysis. In cases where all required safety modifications can be completed during regularly scheduled maintenance, such costs may be the only loss-of-benefits consideration.

Ultimately, as a result of the wide variety of costs that could be incurred as a result of a reactor shutdown, the normal costs of doing business may also change. For example, the utilities' bond rating may be lowered, making overall financing more difficult and expensive, or insurance rates may change. In addition, the utility may be faced with substantial litigation costs as a result of the outage.

2.2.3 Accident-Related Costs

As the accident at Three Mile Island has shown, the potential economic consequences of a reactor accident extend beyond the net replacement energy cost and the financial considerations included in the two previous economic impact categories. Clearly, the financial consequences of more-severe nuclear power plant accidents that affect the health and safety of the general public could be extensive. Figure 2.5 breaks down potential accident-related costs. Off-site costs could include cleanup costs, population relocation and evacuation costs, public and private sector revenues that are lost when business is interrupted (including lost jobs), and costs associated with damaged (e.g., radioactive) goods and property. In addition, the costs of public health effects must be estimated. Substantial litigation costs could also be expected for reactor accidents. Other off-site financial costs may also be important to consider. Many of these potential off-site consequences have been estimated on the basis of CRAC2 (Calculation of Reactor Accident Consequences, Version 2) calculations.[12,13]

The potential on-site costs include not only cleanup and reactor repair costs, but also indirect system costs, such as the costs due to a shutdown of adjacent or other reactors in the pool. The Three Mile Island accident, which involved one unit of a two-unit station, illustrates the importance of this latter category. Although unit 1 was not involved in the accident (it was out of service for refueling at the time), the NRC has not allowed it to return to service. Litigation costs, monies to study case-specific impacts (e.g., psychological stress), and other financial charges, such as fines by the NRC, must also be considered.

2.2.4 Net Health and Safety Impacts

The net health and safety impacts of a reactor outage fall into three categories (Fig. 2.6): impacts associated with replacement fuel use; impacts that result from

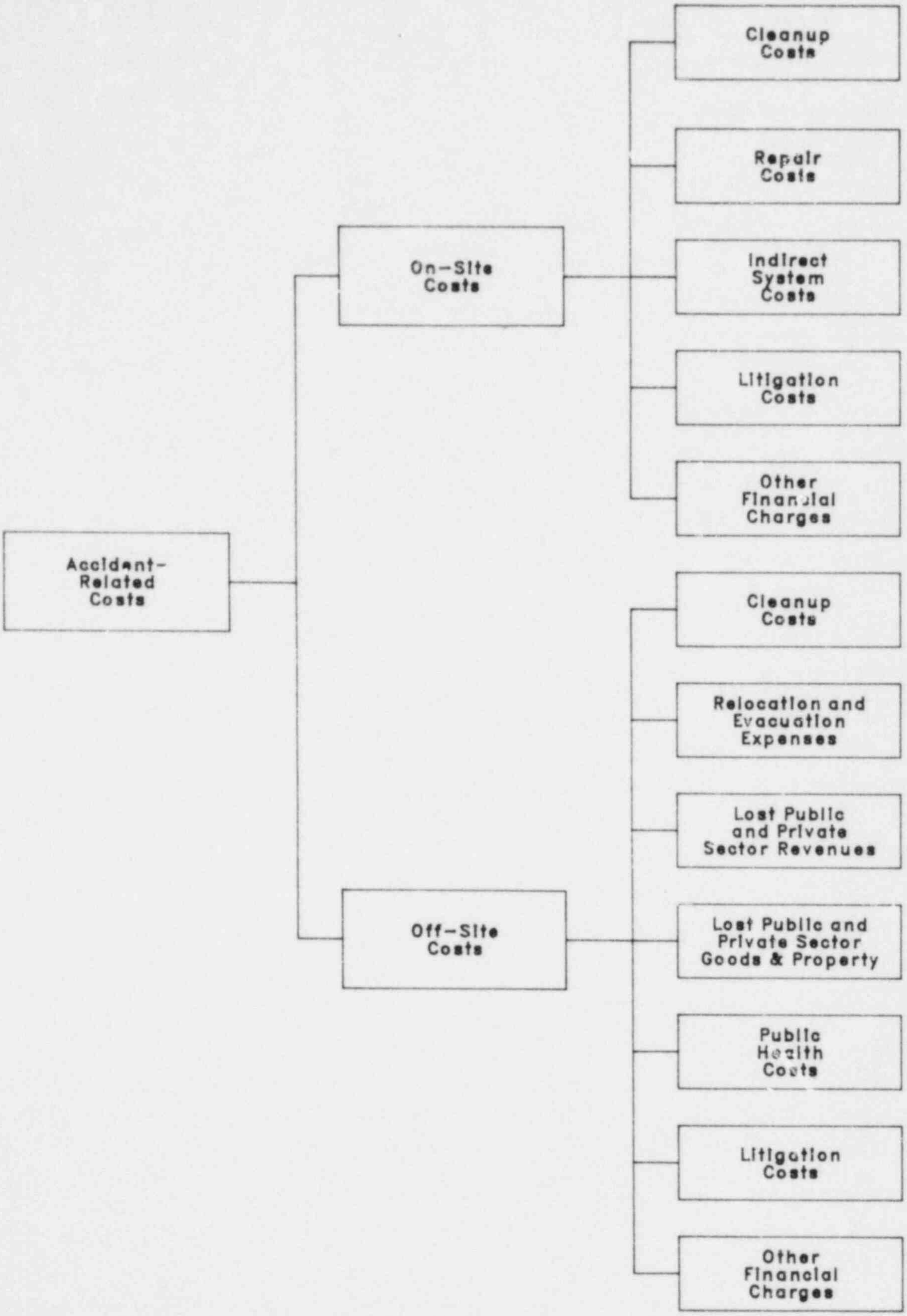

FIGURE 2.5 Breakdown of Accident-Related Costs

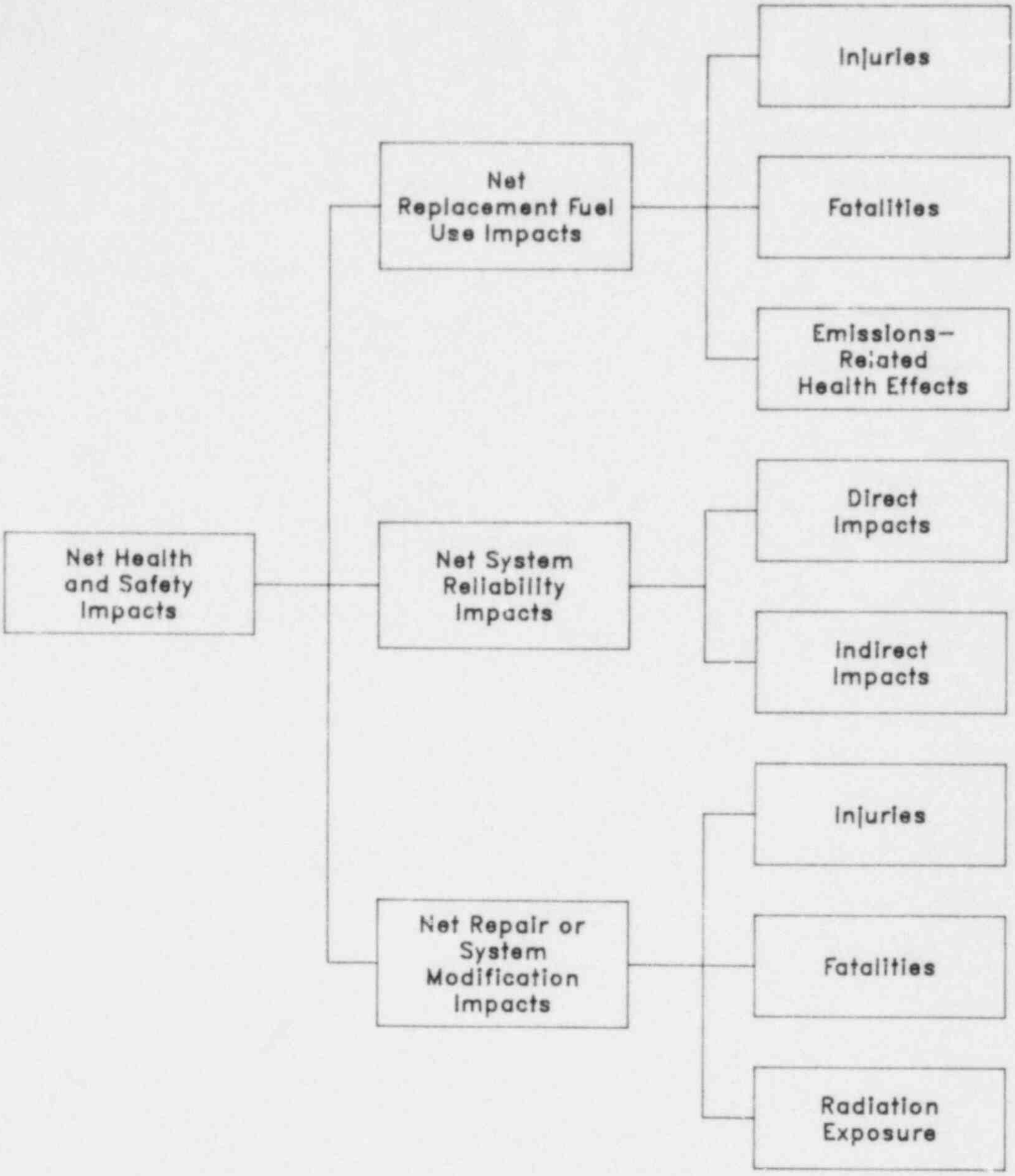

FIGURE 2.6 Breakdown of Net Health and Safety Impacts

changes in system reliability; and impacts associated with reactor repairs, modifications, or other system changes. The use of replacement fuels such as coal causes a wide range of systemwide health and safety impacts -- for example, coal mining accidents, coal transportation accidents, and lung diseases due to coal mining (coal workers' pneumoconiosis). These impacts may exceed those for the nuclear fuel cycle. Therefore, it is important to quantify the net increase (or decrease) in these impacts as compared to those for the nuclear fuel cycle.

It is also important to recognize that health and safety effects may occur both inside and outside of the utility system's service territory. As Fig. 2.6 shows, accidents can generally be classified as fatal or nonfatal. It may also be desirable to classify them as public or occupational. The use of fossil fuels for generating replacement energy can create other potential health impacts such as those associated with sulfur dioxide (SO_2) emissions from the power plants. Lung diseases due to SO_2 emissions affect both occupational workers and the general public.

If a nuclear plant shutdown severely degrades the power system service (e.g., resulting in brownouts or blackouts), it may also directly affect the health and safety of the public. The loss of power in such cases could lead to transportation and traffic problems that result in injuries or fatalities (e.g., loss of traffic signals or malfunctioning railroad crossing guards). The failures of the northeast bulk-power system in the mid-1960s dramatically illustrate the range of potential impacts that could accompany power system outages. Regulatory agencies may allow utilities to bypass pollution control systems, such as scrubbers and electrostatic precipitators, to avoid an interruption in service, thereby indirectly leading to additional health impacts.

Health and safety impacts can also result from reactor repairs or modifications forced by regulations, construction of replacement capacity, or implementation of other strategies to mitigate the effects of a reactor shutdown (e.g., upgrading interconnections). Three primary categories of impacts are identified in Fig. 2.6: injuries, fatalities, and radiation exposures. To a large extent, these categories represent occupational health and safety risks.

2.2.5 Net Environmental Impacts

The environmental effects of a shift in fuel use are numerous and wide-ranging. Increased SO_2 emissions that result from increased use of coal or high-sulfur fuel oil, for example, may damage vegetation and man-made structures in both local and distant regions (e.g., from acid deposition). Increased carbon dioxide (CO_2) emissions may have significant long-range effects on global climate. Solid waste disposal would increase with coal use, as would the amount of land disturbed for surface mining if the coal were strippable. All of these impacts should be calculated and compared to the impacts that would occur when the reactor is operating.

2.2.6 Net Socioeconomic Impacts

The net socioeconomic impacts of a reactor shutdown can be broken down into local impacts and systemwide impacts, as shown in Fig. 2.7. On a local level, a permanent reactor shutdown would lead to lost jobs at the plant (primary employment) and possibly in the surrounding communities (secondary employment). Because these communities are typically small (for safety reasons, reactors are built away from large population centers), the impacts on employment and business in general could be severe. Tax revenues from the plant, which are usually substantial, would also be lost if the shutdown were permanent. In the long term, power shortages and higher electricity costs caused by a reactor shutdown could discourage new businesses from locating in a region, and some existing businesses could be forced to move to regions where power supplies are cheaper and more reliable.

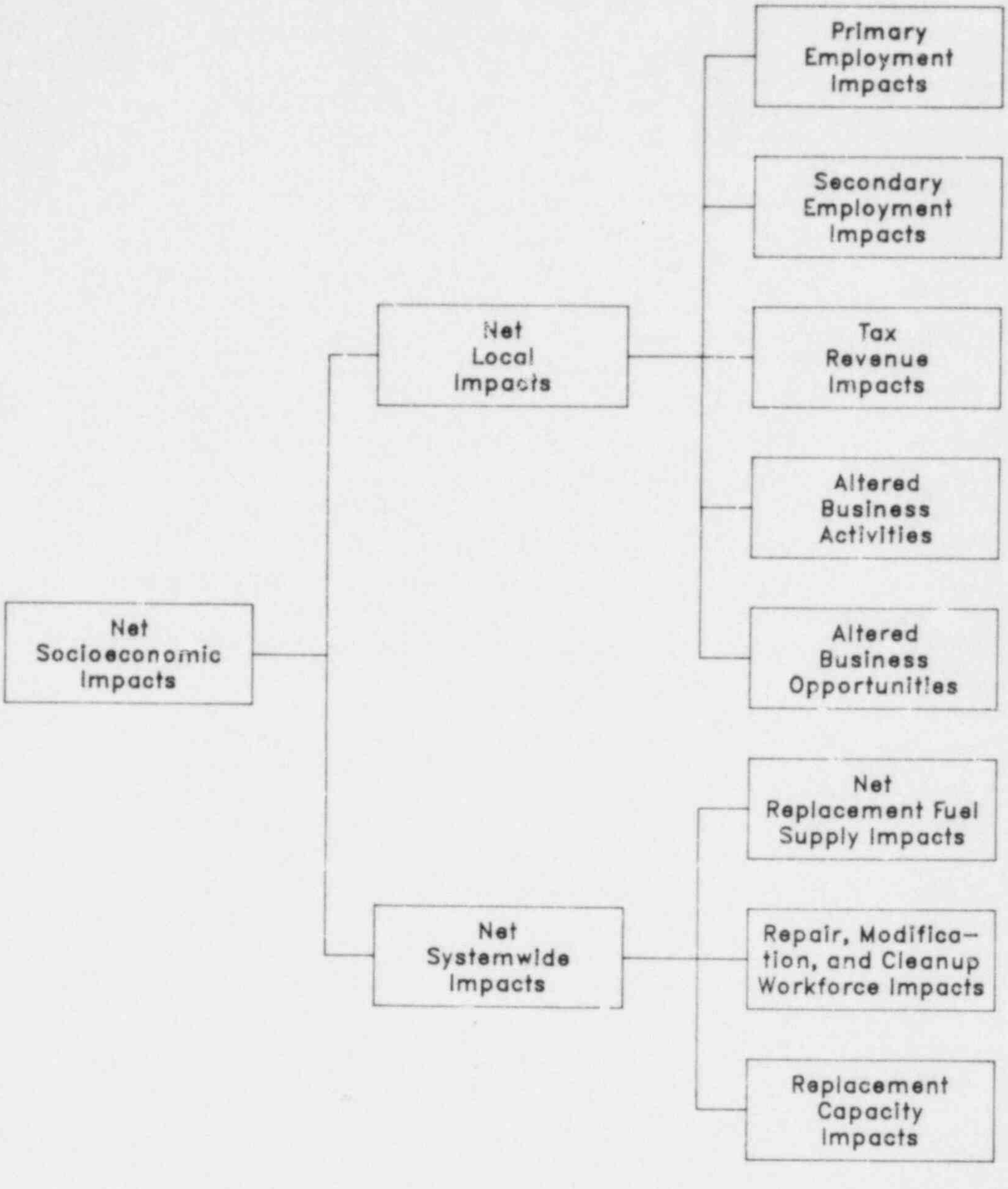

FIGURE 2.7 Breakdown of Socioeconomic Impacts

Systemwide, the net socioeconomic impacts include impacts from changes in fuel use patterns, such as the impacts on mining communities due to the use of replacement fuels such as coal, and impacts from the temporary influx of workers for plant repairs, cleanup, or modifications. If a utility decides to build a new generating facility to replace a reactor that is permanently shut down, for example, the net socioeconomic impacts of that decision must also be considered.

2.2.7 Accident-Related Impacts

Like the breakdown of accident-related costs shown in Fig. 2.5, the noneconomic accident-related impacts can be divided into two categories: on-site impacts and off-site impacts. In both cases, the broad range of impacts can be classified as health and safety impacts, environmental impacts, and socioeconomic impacts. The on-site health and safety impacts, which can be defined as early deaths, early injuries, and latent cancer fatalities, primarily involve occupational personnel, while the off-site health and safety impacts involve the public. Models such as CRAC2, which is an improved version of the code originally developed for the Reactor Safety Study, can be used to calculate radiation dose to the public.[12] The calculated dose should account for both external exposure to airborne and deposited radionuclides and internal exposure to inhaled and ingested radionuclides. The wide-ranging consequences of reactor accidents are discussed in Refs. 13 and 14.

2.3 LOSS OF BENEFITS IN REGULATORY DECISION MAKING

The impacts that accompany nuclear power plant accidents and regulatory actions such as licensing delays or shutdowns are (as shown in the previous section) diverse and potentially costly. The importance of any particular impact or loss of benefits, however, cannot be generically determined, but must instead be evaluated on a case-by-case basis. Within this case-specific context, regulatory decision making can be viewed as balancing the risks of continued reactor operation against the loss of benefits that may result from a particular regulatory action taken to reduce those risks. This concept is illustrated in Fig. 2.8, which shows a simplified decision tree of a regulatory decision problem.

The premise for the decision problem illustrated in Fig. 2.8 is that, because a reactor fails to meet some type of quantitative safety criteria, the NRC must decide whether it will allow the plant to continue operating or shut the reactor down for modifications.* The fundamental decision problem, therefore, becomes one of evaluating

(1) The incremental reduction in risk that results from a particular safety modification, and

(2) The loss of benefits that would result from the shutdown required to make the modification.

The decision maker must then balance the reduction in risk against the loss of benefits. This balancing requires, in addition to quantitative data on risks and loss of benefits, a comprehensive and defensible method.

In the simplest of cases, when one assumes that all important risk and loss-of-benefits considerations can be measured in a dollar metric, a straightforward benefit-cost approach might be appropriate. For example, if the incremental reduction in risk that results from a specific safety modification for a reactor could be expressed as

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*A broader set of options, involving alternative shutdown strategies (including permanent shutdowns) and different types of reactor modifications, would normally be considered. The greater number of alternatives would only reinforce the need for and value of the decision analysis approach outlined in this section.

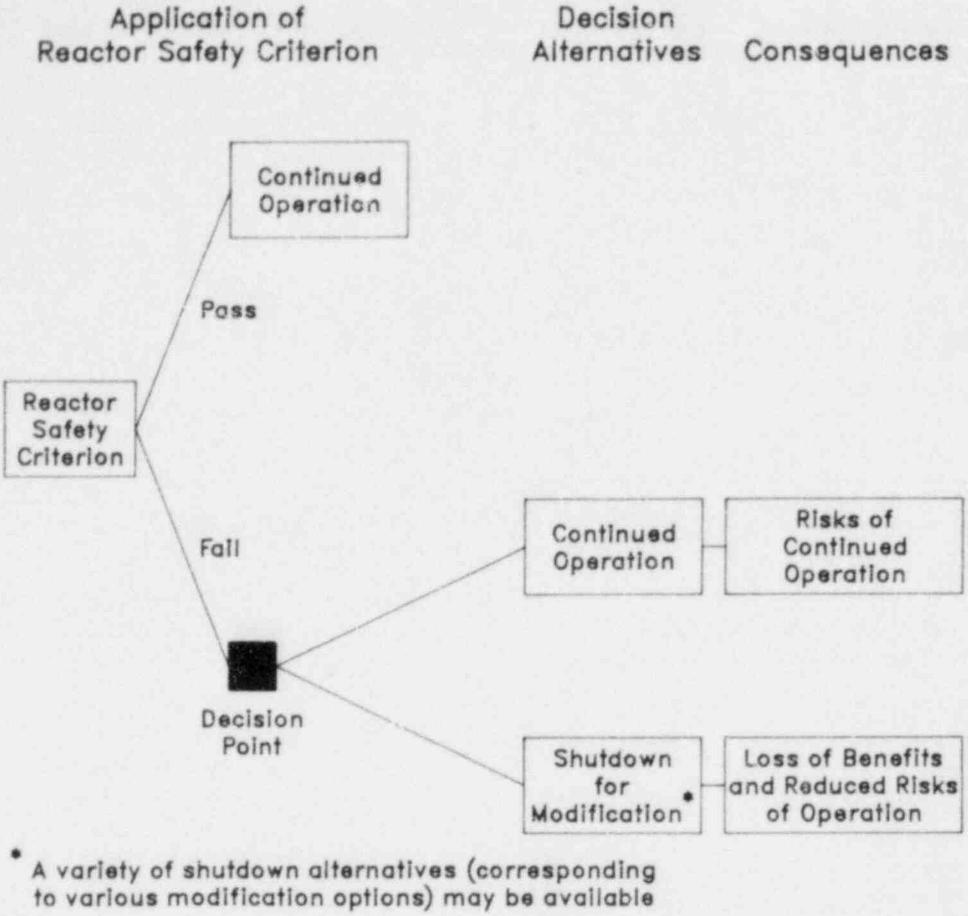

FIGURE 2.8 Simplified Representation of Regulatory Decision Problem

$$\text{Incremental Reduction in Risk (man-rem)} = E - E' \tag{2.1}$$

where

E = Expected population exposure before proposed safety modifications have been implemented (man-rem), and

E' = Expected population exposure after proposed safety modifications have been completed (man-rem),

and a benefit-cost coefficient, M_t (\$/man-rem averted), could be defined (as in Ref. 15) for a reduction in expected population exposure, then the benefit (in \$) at time t of an incremental reduction in risk could be determined:

$$\text{Benefit at time t of risk reduction (\$)} = M_t(E - E') \tag{2.2}$$

where

M_t = Benefit-cost coefficient (at time t) for a safety modification that reduces expected population exposure (\$/man-rem averted).

The benefit-cost coefficient can be expressed using continuous compounding:

$$M_t = M_o e^{ct} \tag{2.3}$$

where

M_o = Benefit-cost coefficient at time zero (\$/man-rem averted), and

c = Effective rate of continuous compounding (fraction).

Sophisticated probabilistic risk assessment (PRA) techniques are being used to estimate population exposure (i.e., E and E'); proposed values of M_o typically range from about \$100-1000/man-rem averted.[15,16]

If every loss of benefits (Fig. 2.2) could be measured in a dollar metric and all component costs aggregated into either short-term costs (C_t^s) that are incurred during the outage or long-term costs (C_t^ℓ) that are incurred over the remaining reactor life after the modifications have been completed, then the discounted costs of the outage (i.e., the loss of benefits expressed in monetary terms) can be expressed as follows:

$$\begin{matrix}\text{Discounted} \\ \text{Costs (\$)}\end{matrix} = \int_{\substack{\text{outage} \\ \text{period}}} C_t^s e^{-rt} dt + \int_{\substack{\text{remaining} \\ \text{life}}} C_t^\ell e^{-rt} dt \tag{2.4}$$

where

C_t^s = All costs (loss of benefits) occurring at time t during outage period (\$),

C_t^ℓ = All costs (loss of benefits) occurring at time t over remaining operating life of reactor (\$), and

r = Effective discount rate for benefit and cost streams using continuous compounding (fraction).

With these results, the benefit-cost criterion for making a proposed safety modification can be defined as follows:

$$\frac{\text{Discounted Benefits}}{\text{Discounted Costs}} = \frac{M_o \int_{\substack{\text{remaining}\\ \text{life}}} (E - E')e^{ct}e^{-rt}dt}{\int_{\substack{\text{outage}\\ \text{period}}} C_t^s e^{-rt}dt + \int_{\substack{\text{remaining}\\ \text{life}}} C_t^\ell e^{-rt}dt} \qquad (2.5)$$

When the value of Eq. 2.5 is greater than 1.0, the benefit (i.e., the incremental reduction in risks) of the proposed modification is greater than the cost (i.e., the loss of benefits), and thus the modification should be made. When the value of Eq. 2.5 is less than 1.0, however, the modification is not justified by a strict interpretation of the benefit-cost criterion.

While Eq. 2.5 may be appealing because of its relative simplicity, its usefulness is extremely limited in practice. As highlighted in the previous section, the wide-ranging and uncertain loss-of-benefits impacts are measured in noncommensurate units that include not only costs, but also fatal and nonfatal accidents and illnesses, latent cancers, SO_2 and CO_2 emissions, and property damage. In addition, nonquantified loss-of-benefits considerations such as psychological stress and public acceptance of nuclear power may be crucial factors in a decision. From a decision standpoint, these impacts typically represent a set of multiple conflicting objectives. For example, a decision maker may wish to simultaneously maximize public acceptance and minimize costs, fatalities, and emissions. In most cases, no single alternative is the best with respect to all of the objectives identified. The decision problem then becomes one of value tradeoffs, that is, deciding how much should be given up with respect to one objective to achieve a specified improvement in another.

The decision problem is further complicated by individual preferences and risk attitudes that affect the choice of action. Some individuals and groups, for example, will pay more to avoid accidents with low probability and severe consequence than to avoid less-serious accidents with the same expected values for fatalities. Decision analysis, unlike benefit-cost analysis,[17] provides a methodological basis for treating these important complexities.

Decision analysis is a systematic and quantitative technique for organizing and processing information to aid decision making in an environment of uncertainty.[18] It is based on a set of logical axioms implying that the attractiveness of alternatives should depend on (1) the likelihoods of the possible consequences of each alternative and (2) the preferences of the decision makers for those consequences. Unlike benefit-cost analysis, which requires that consequences be measured in a common metric such as dollars, decision analysis uses a utility function to provide the common metric. The units of the utility function capture the decision maker's risk attitudes and preferences for consequences. The utility function measures the decision maker's degree of satisfaction with a particular alternative. In cases of multiple alternatives (such as the decision problem illustrated in Fig. 2.8), the utility function is an appropriate guide for decision making; the best course of action is the alternative that maximizes the expected value of the utility function.

The concept of utility is illustrated in Fig. 2.9 for the regulatory decision problem introduced in Fig. 2.8. On the basis of the consequences of each decision alternative, the decision maker must establish a set of objectives that can be used to measure the desirability of the alternatives. The degree to which the objectives are met is measured by a set of attributes that correspond to each objective. For example, the objective "minimize fatalities" might simply be measured by the number of fatalities, which for any particular alternative can be expressed as a probability distribution. Subjective scales can be constructed to measure an unquantified loss of benefits. Therefore, a set of attributes, denoted $X = (X_1, X_2, ..., X_n)$ and corresponding to the set of n objectives established for the problem, can be used to measure the consequences of each alternative. As Fig. 2.9 shows, the consequences of continued reactor operation are defined by the attribute levels denoted X', while the consequences of shutting the reactor down for modifications and then continuing operation are defined by the attribute levels denoted X".

If U(X) denotes a utility function over the set of attributes X, where the utility function models the decision maker's preferences for the consequences of each alternative, then the risk of continued operation is preferred to a shutdown for modification only if

$$U(X') > U(X'') \qquad (2.6)$$

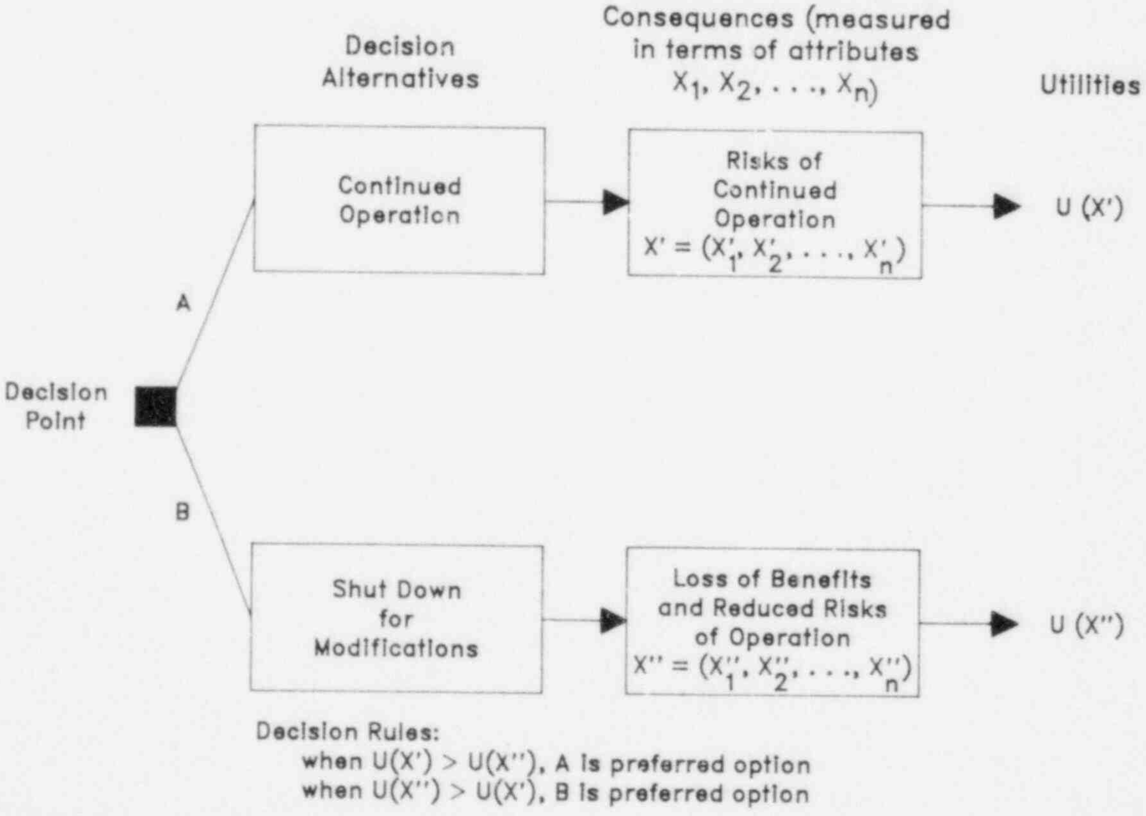

FIGURE 2.9 Quantifying Degree of Satisfaction for Alternatives with a Utility Function, U(X)

Conversely, the shutdown is preferred to continued operation if

$$U(X'') > U(X') \tag{2.7}$$

The procedure for quantifying an individual's utility function [i.e., U(X)] involves systematically eliciting relevant information about value tradeoffs and risk attitudes. These concepts are discussed in detail in Keeney and Raiffa (Ref. 18).

In summary, the methodology of decision analysis explicitly recognizes uncertainties and subjective judgments, provides a framework for systematically and comprehensively analyzing complex decision problems, and supplies a well-documented and defensible basis for decisions. The underlying philosophy of the method is that the desirability of an alternative should depend on both (1) the likelihoods that the alternative will lead to various consequences and (2) the decision maker's preferences for those consequences. In general, decision analysis is a robust method for analyzing complex decision problems like that shown in Fig. 2.8; benefit-cost methods (and their variants) are simplifications of this general approach.

3 CASE STUDY DEFINITIONS

This section describes the key assumptions and initial conditions that were used in the loss-of-benefits case study presented in Sec. 4. Most of the initial conditions and assumptions are based on the default data in Argonne's detailed data base of electrical utility systems (ADAP). For perspective, a brief overview of the New York Power Pool, which was selected for this illustrative loss-of-benefits case study, is also provided.

3.1 CASE STUDY APPROACH

Many loss-of-benefits considerations were identified, briefly described, and categorized in Sec. 2.2. The applicability of these considerations depends on the cause of the outage (e.g., accident or regulatory action) as well as the specific characteristics of the reactor and power pool being analyzed. Different types of data and models are required to comprehensively analyze all the effects of a reactor shutdown, particularly shutdowns that result from a reactor accident.

The illustrative case study presented in this report analyzes only the production-cost impacts of long-term reactor shutdowns and the risks of replacement fuel use. In all cases, the hypothetical reactor outages examined were assumed to result from a regulatory action. Argonne's production-cost and reliability model (ICARUS) was used for all system simulations; initial conditions and system representations were drawn from ADAP, the extensive data base developed to interface with ICARUS (Fig. 3.1). Systems were simulated for a 10-year study period (five-year period for the multiple-shutdown sensitivity study) beginning January 1, 1984. The New York Power Pool was selected to illustrate the loss-of-benefits approach and demonstrate the model's capabilities and flexibility. The Fitzpatrick reactor was chosen for the single-reactor shutdown analyses. This 810-MW, General Electric boiling-water reactor began commercial operation in July 1975. The impacts of closing two other reactors in this power pool (Indian Point Units 2 and 3) were extensively studied previously in response to general safety concerns and Atomic Safety and Licensing Board hearings.[19,20]

As briefly described in Sec. 1.2, production-cost effects of reactor outages are estimated in this study by comparing the results of two simulations based on a common set of assumptions:

1. A case in which all generating units in the power pool, including the reactor (or reactors) of interest, are assumed to operate normally (base case), and

2. A case in which the designated reactor is assumed to be unavailable for generation (shutdown case).

Assumptions about the power pool and the generating units in the pool are identical in both the base and shutdown cases. Both fixed and variable O&M costs for the designated reactor are treated as avoided costs in the shutdown case for the entire study period

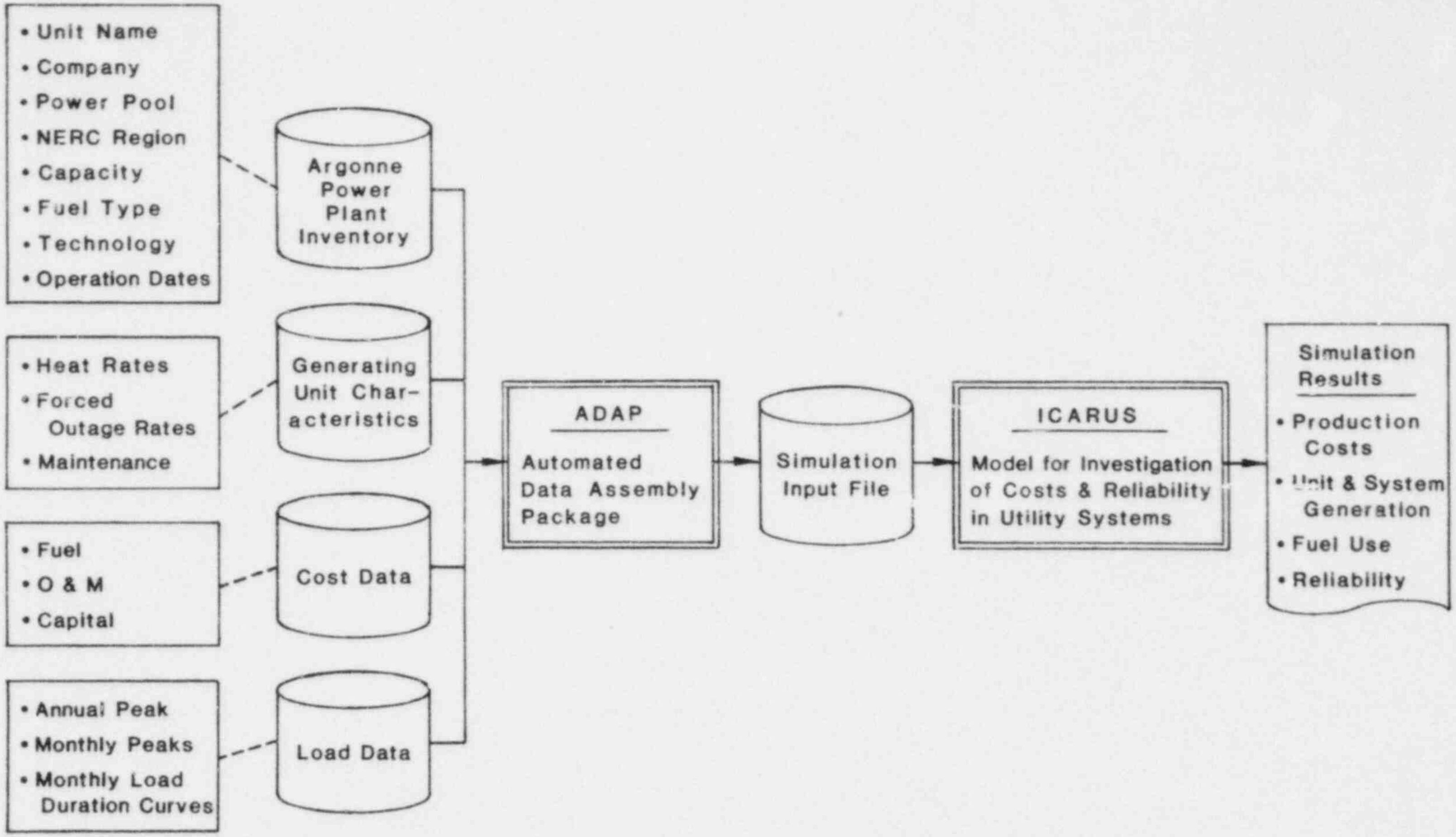

FIGURE 3.1 Interface between ADAP and ICARUS

(i.e., there are no O&M costs for the affected reactor in the shutdown case). As described in Sec. 2, this assumption decreases the magnitude of the cost difference between the base and shutdown cases. For a short-term shutdown of a nuclear unit, the fixed O&M costs would normally be included in the shutdown case.

To ensure a consistent basis for comparing the base and shutdown cases, no adjustments in system operations (i.e., mitigation strategies) were allowed in the shutdown cases. In actual nuclear plant shutdowns, however, the affected utility would probably implement measures that would minimize the potential effects of the outage on system operations and customers. For example, if the utility expected the outage to last for several years, it probably would reoptimize its overall maintenance schedule, while for long-term or permanent shutdowns, the utility would also reoptimize its overall capacity expansion schedule. Such reoptimizations of the capacity expansion schedule are complex and, as discussed in Sec. 2, require the use of an optimizing capacity expansion model. In general, mitigation responses can significantly affect loss-of-benefits results. In the longer term, shutdown costs are lower when such mitigation measures are taken.

3.2 OVERVIEW OF THE NEW YORK POWER POOL

The New York Power Pool (NYPP) is a member of the Northeast Power Coordinating Council (NPCC) region,* which also includes Ontario, New Brunswick, and six New England states. The pool coordinates the planning and operation of the seven major investor-owned electric utilities in New York State** along with the Power Authority of the State of New York. The NYPP is unique in that it is the only integrated operating system in the contiguous United States that covers an entire state.[21] The pool provides a transmission link for transporting power to New England from both Canada and the coal-burning plants of the western United States. A 765-kV transmission line carries the heavy imports of Canadian hydroelectric power into the region. The NYPP is the major importer of Canadian power for the eastern United States.

Historically, the NYPP has relied heavily on oil, particularly imported oil, for electricity production. In 1982, petroleum was used to produce about 30% of the electricity required in the NYPP, compared to only 6% for the United States as a whole.[21,22] The economic cost and vulnerability to disruption resulting from this reliance on foreign oil have led to numerous energy policies aimed at shifting to less-costly and more-secure energy sources. Increasing the use of natural gas for generating electricity and increasing electricity purchases from Canada (primarily from hydroelectric sources) have reduced oil consumption in the NYPP from 89 x 10^6 bbl in 1978 to 56 x 10^6 bbl in 1982, a 37% decrease.

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*One of the nine North American Electric Reliability Council regions.

**Central Hudson Gas & Electric Corp.; Consolidated Edison Co.; Long Island Lighting Co.; New York State Electric & Gas Corp.; Niagara Mohawk Power Corp.; Orange and Rockland Utilities, Inc.; and Rochester Gas & Electric Corp.

In 1980, approximately 12% of the total net dependable capacity in the pool was nuclear, 11% coal, 13% hydroelectric, 3% pumped storage, 14% gas turbine, and 47% oil steam. Table 3.1 identifies the five nuclear generating units that operated in 1980. In terms of actual generation, the nuclear units provided 17% of the kilowatt-hours supplied in 1980, coal plants 17%, hydroelectric plants 24%, oil-fired plants 32%, and gas-fired plants 10%. The system load factor in 1980 was 62%. The pool operates on an established planned reserve criterion of 22% to cover scheduled and unscheduled generation outages, although the reserve margin during the 1980 summer peak was over 40%. Because the NYPP plans to have reserve margins that are greater than the established reserve criterion through 1993, the loss of one reactor is not expected to cause severe reliability problems. This situation is not typical of power pools in most other regions of the United States. A number of the major generating facilities and other characteristics of NYPP are shown in Fig. 3.2.

3.3 ASSUMPTIONS AND INITIAL CONDITIONS

Load Growth

One of the major considerations in determining unit operation and the need for additional generating capacity or energy is load growth. The load growth assumed in this case study for the 1984-1993 study period was 1.7%/yr. At this rate of growth, annual electricity consumption increases from 118×10^9 kWh in 1984 to 138×10^9 kWh in 1993, which corresponds to the 1982 projection made by the NYPP members.[23] This forecast assumes slow economic recovery and more-intense load management by consumers, although the rate of growth is slightly higher than the 1.5%/yr average experienced by the pool over the 1972-1980 period. Demands in the pool decreased from a peak of about 119×10^9 kWh in 1980 to slightly over 117×10^9 kWh in 1982.[22] Alternative load-growth scenarios were investigated in the sensitivity studies.

Oil Displacement

To decrease its dependence on foreign oil use, NYPP has adopted a strategy of increasing energy purchases from Canada, converting nearly 3000 MW of oil-fired capacity to coal-fired capacity, and constructing new nonoil generating capacity. Currently, NYPP expects to purchase approximately 18×10^9 kWh (firm and economy purchases) each year from Canada (Hydro Quebec and Ontario Hydro) over the 1984-1997 period.[22] The level of imports assumed in the base case approximates this 18×10^9 kWh/yr level.

Converting oil-fired units to coal-fired units represents one of the most direct short-term steps that can be taken to reduce oil consumption in the state. The planned generating-unit conversions reported by the NYPP in its 1983 annual report were assumed in the case study. The specific units affected, capacities before and after conversion, and the time frames over which the conversions take place are listed in Table 3.2. The unit conversions will take from one to eight months to complete. In some

TABLE 3.1 Nuclear Generating Capacity in NYPP

Unit	Location	Utility	Reactor Type[a]	Size (MW)	Date of Commercial Operation
Nine Mile Point 1	Scriba, N.Y.	Niagara Mohawk Power Corp.	General Electric BWR	610	Dec. 1969
Ginna 1	Ontario, N.Y.	Rochester Gas & Electric Corp.	Westinghouse PWR	470	March 1970
Indian Point 2	Buchanan, N.Y.	Consolidated Edison Co.	Westinghouse PWR	849	July 1974
Fitzpatrick	Scriba, N.Y.	PASNY	General Electric BWR	810	July 1975
Indian Point 3	Buchanan, N.Y.	PASNY	Westinghouse PWR	965	Aug. 1976

[a] BWR = boiling-water reactor; PWR = pressurized-water reactor.

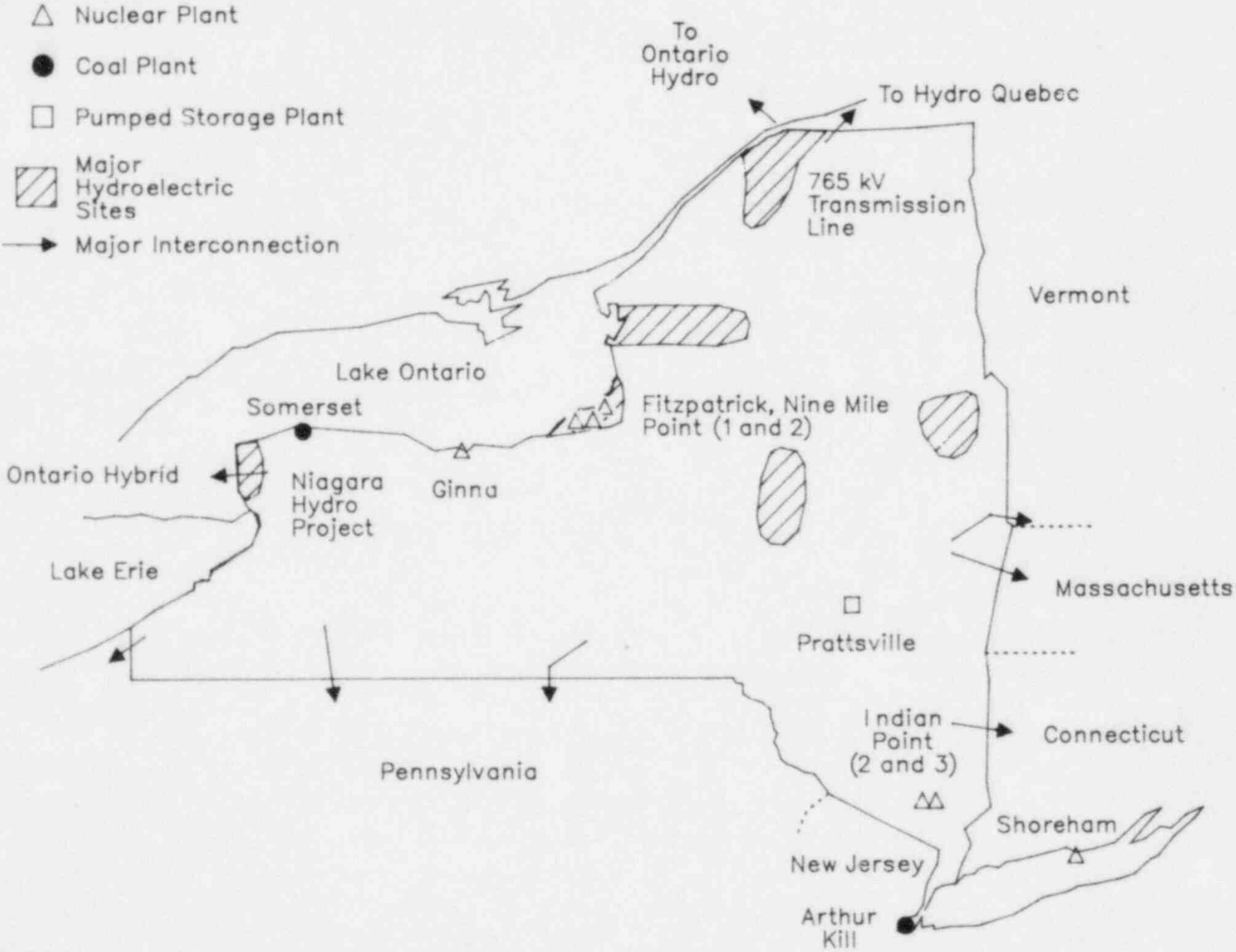

FIGURE 3.2 Major Generating Facilities in NYPP

TABLE 3.2 Planned Generating-Unit Conversions (Fuel Oil to Coal) for NYPP (1983-1992)

Facility	Capacity before Conversion (MW)	Removal Date	Return Date	Capacity after Conversion (MW)
Ravenswood	928	11/83	12/83	928
Lovett 5	202	8/84	10/84	196
Lovett 4	197	10/84	1/85	191
Arthur Kill 3	491	5/86	7/86	491
Arthur Kill 2	335	9/86	12/86	335
Danskammer 3	126	5/86	9/86	133
Port Jefferson 3	190	4/87	1/88	186
Danskammer 4	227	4/88	9/88	230
Lovett 3	63	10/88	1/89	63
Port Jefferson 4	190	4/88	1/89	186
Total				2939

Source: Refs. 22 and 23.

cases, a slight derating of capacity is expected. All the generating units undergoing conversion will burn high-sulfur eastern coal in place of oil.

The major new nonoil capacity additions reported in the NYPP 1983 annual report were assumed in the case study as specified in Table 3.3. Two large coal-fired generating units (Somerset and Arthur Kill) with a combined capacity of 1325 MW and two nuclear units (Shoreham and Nine Mile Point Unit 2) with a combined capacity of 1889 MW are scheduled for the 1984-1990 period.* Shoreham and Somerset, scheduled for operation in late 1986, are currently under construction. A 1000-MW pumped-storage hydroelectric facility (Prattsville), scheduled for operation in late 1989, is planned by PASNY. A number of small hydroelectric and refuse-burning facilities will provide an additional 281 MW of capacity over the 1984-1993 study period.

Figures 3.3 and 3.4 show the expected capacity mix (measured in megawatts) for the NYPP at the ends of 1984 and 1993, respectively. As indicated in Fig. 3.3, the region depends heavily on expensive oil-fired capacity; over half of all capacity in the pool burns oil. Six nuclear power plants (listed in Table 3.1) account for about 14% of all generating capacity; coal-fired units, most of which are located in the northern portion of the state, account for about the same percentage. Over 3900 MW of hydroelectric

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*Since the completion of this study, the Long Island Lighting Co. has revised the scheduled start-up date for Shoreham. It is anticipated that the unit will be delayed by perhaps a year or longer from the assumed January 1984 start-up.[24]

TABLE 3.3 Planned Generating-Unit Additions for NYPP[a] (1983-1992)

Facility	Type	Size (MW)	In-Service Date
Shoreham[b,c]	Nuclear	809	1/84
Somerset[b]	Coal	625	11/84
Nine Mile Point 2[b]	Nuclear	1080	11/86
Prattsville[d]	Pumped storage	1000	9/89
Arthur Kill[d]	Coal	700	5/90
Total		4214	

[a] List does not include 20 small hydroelectric plants (149 MW), three refuse-burning facilities (112 MW), and one wood-burning plant (20 MW) planned for the 1983-1992 period.

[b] Under construction.

[c] Start-up date has changed since the completion of this study.[24]

[d] Planned.

Source: Ref. 22.

power (representing over 100 hydroelectric power generating units) and nearly 1300 MW of pumped storage capacity are also available in the state. Overall, the generating stations operating at the end of 1984 have a combined capacity of nearly 32 x 10^6 kW.

Together, Figs. 3.3 and 3.4 illustrate how the mix of system generating capacity shifts over the study period due to the unit additions, retirements, and conversions. Coal-fired units account for 21% of all generating capacity by the end of 1993, while oil-fired units account for about 44%. The percentages of nuclear and hydroelectric capacity remain fairly constant. A combined generating capacity of over 34 x 10^6 kW is available at the end of the year.

Prices and Escalation Rates

The fuel prices specified in ADAP were used in the case study. This consistent set of prices, expressed in 1983 dollars, was developed on the basis of regional cost estimates (as outlined in Ref. 7) and represents generic data rather than actual unit-specific data. The fossil fuel prices are based on the delivered fuel prices for electric

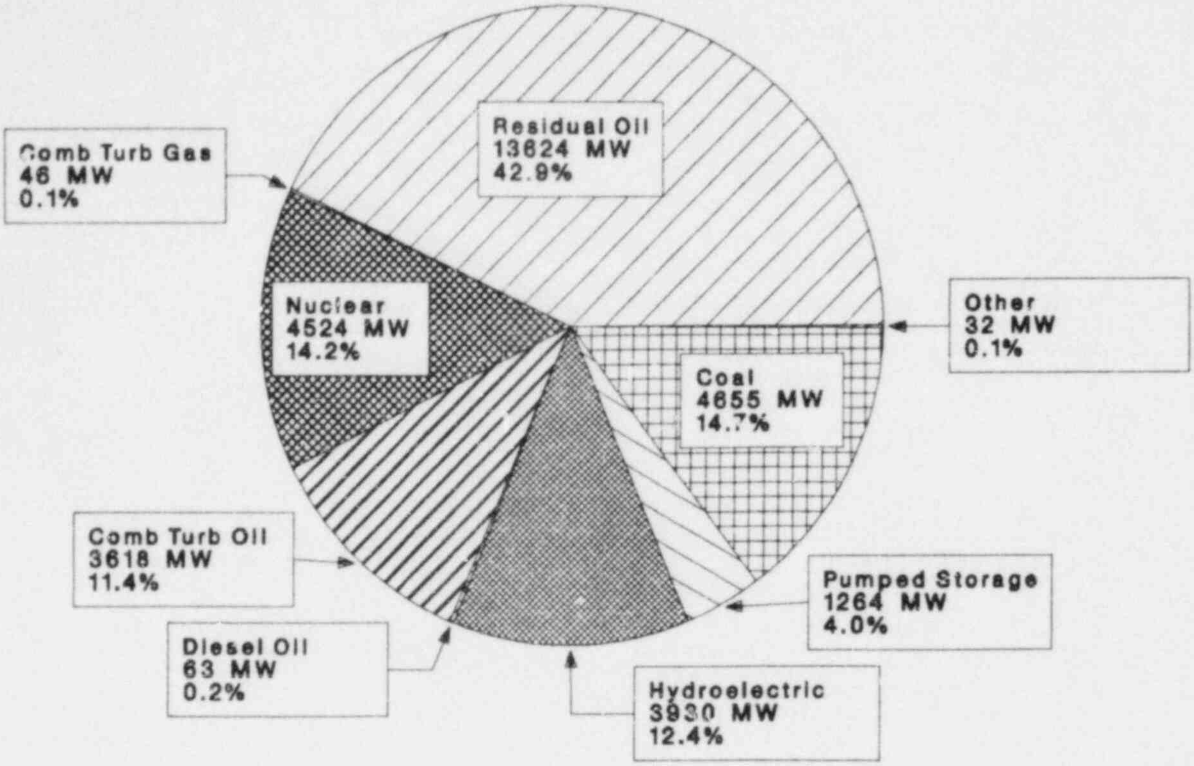

FIGURE 3.3 Expected NYPP Capacity in 1984

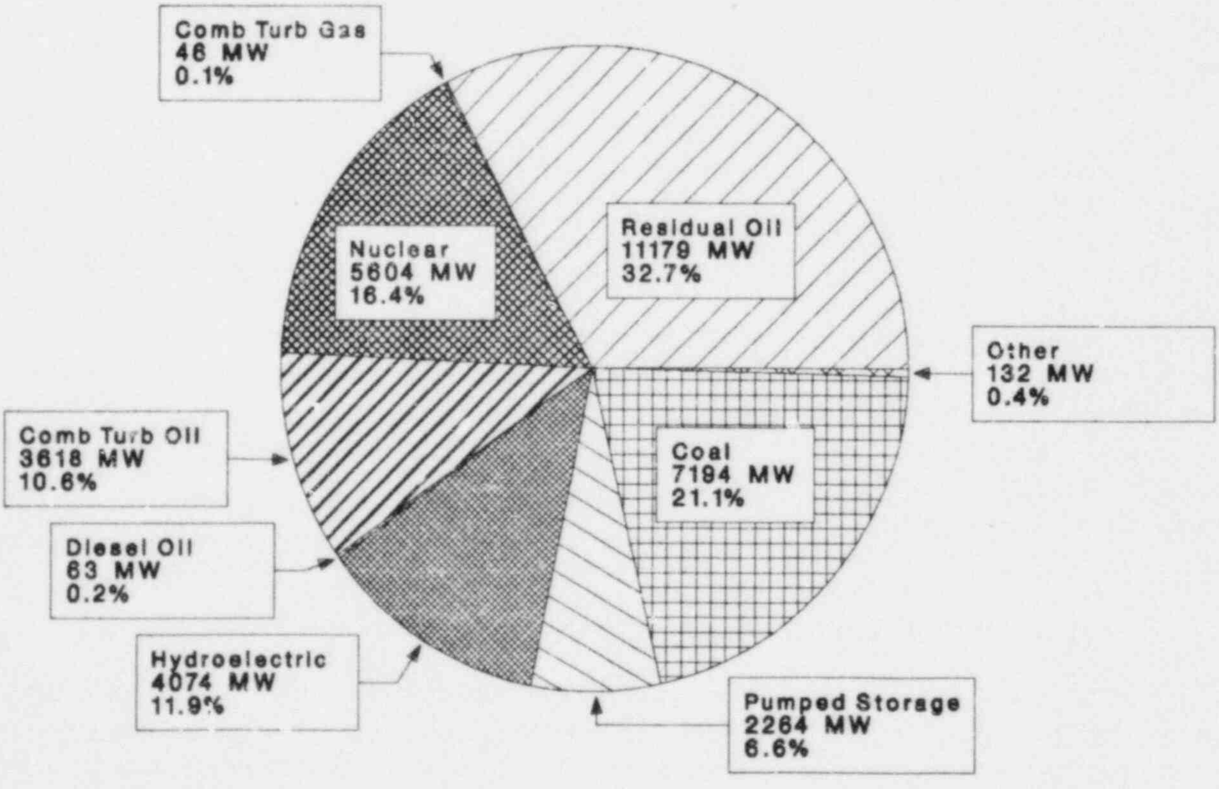

FIGURE 3.4 Expected NYPP Capacity in 1993

utilities as reported annually by the U.S. Department of Energy,[25] while the nuclear fuel costs are based on Electric Power Research Institute estimates.[26]

Table 3.4 summarizes the energy costs assumed in the case studies. The costs for the different categories of energy purchases were developed using the fuel prices in Table 3.4 as a guide. The cost of firm purchases is slightly higher than the cost of generation using all coal units, the cost of economy purchases represents an average of the costs for oil (residual) and coal generation, and the cost of emergency purchases approaches the cost of combustion-turbine generation. These purchase prices are for a "typical" quantity of purchases; obviously unlimited economy purchases at \$40/MWh are not available.

The fixed and variable O&M costs used in the case study also corresponded to the costs specified in ADAP. The fixed O&M costs for coal and oil vary according to the type and size of the generator. For example, high-sulfur coal units with capacities of 300-500 MW have fixed O&M costs of either \$10.4/kW-yr or \$19.0/kW-yr, depending on whether they have flue-gas desulfurization (FGD) systems. Oil steam units in the same capacity range cost \$2.1/kW-yr. The fixed O&M costs (in \$/kW-yr) for all sizes of nuclear, combustion turbine, diesel, hydroelectric, and pumped storage units are 36.0, 0.3, 8.1, 2.1, and 2.1, respectively. Variable O&M costs for the different types of units in the NYPP are shown in Table 3.5. There are no variable O&M costs associated with hydroelectric and pumped storage units.

No real price escalation was used in the case study except for the natural gas price, which was assumed to escalate to 90% of the residual oil price by 1985 to reflect the effects of price decontrols. This assumption of zero real escalation provides a

TABLE 3.4 Fuel and Energy Costs for Case Study (first-quarter 1983 dollars)

Type	Cost
Fuels (¢/10^6 Btu)	
Nuclear	98
High-sulfur coal	197
Natural gas	411
Residual oil	467
Distillate oil	671
Purchases (\$/MWh)	
Firm	30
Economy	40
Emergency	79

TABLE 3.5 Variable O&M Costs for Case Study (first-quarter 1983 dollars)

Unit Type	Variable O&M Cost (\$/MWh)
Nuclear	0.2
Oil steam	2.1
Gas steam	2.1
Combustion turbine	3.7
Diesel	8.6
High-sulfur coal	
with FGD	4.8
without FGD	1.4

Source: Ref. 7.

consistent basis for comparing the effects of nuclear unit shutdowns. The sensitivity analysis described in Sec. 5 examined the effects on production costs of different rates of real fuel price escalation. Differential escalation rates were also investigated for cases in which oil prices were assumed to escalate at a substantially higher rate than the other fuel prices.

Capacity Factors

The capacity factors calculated for the generating units in the NYPP are based on the generic forced outage rates and scheduled maintenance requirements specified in ADAP. The equivalent forced outage rate in the data base for nuclear units is 21.7%, and the annual maintenance period (for both refueling and routine servicing) is 10 weeks. For a single block representation of a nuclear unit, these values result in a capacity factor of about 63%.* For the two-block nuclear plant representation used in ICARUS, the resultant capacity factor for all nuclear units is about 57%. This generic nuclear capacity factor is close to the national average, but may not represent any particular nuclear unit. For example, the lifetime average capacity factor for Nine Mile Point 1 is 57.7%, but for Ginna it is about 69% and for Indian Point 3 it is 49%.[27] Fitzpatrick's lifetime capacity factor is 63.1%.[27] Because capacity factor assumptions tend to be the focus of considerable attention, the effects of higher and lower values are investigated in the sensitivity studies.

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*63% = (1 - 0.217)(8760 - 1680)/8760, where 8760 = number of hours per year and 1680 = number of hours in 10 weeks.

4 EFFECTS OF FITZPATRICK SHUTDOWN

This section summarizes the loss of benefits that would result from a hypothetical long-term shutdown of the Fitzpatrick Nuclear Station. The results of this illustrative case study focus on net replacement energy costs and generating system reliability, which were calculated using ICARUS, and the net risks of replacement fuel use.

4.1 BASE CASE GENERATION AND FUEL USE

The expected generation (including purchases) for the first and last years in the study period (measured in percentage of total kilowatt-hours generation) is displayed in Figs. 4.1 and 4.2, respectively. This generation, which results from the system representations shown in Figs. 3.3 and 3.4, corresponds to normal operation of all reactors in the pool, including Fitzpatrick (i.e., base-case generation). The breakdown of expected generation for 1984 (Fig. 4.1) shows that oil-fired units supply about 28% of all kilowatt-hours generated (112×10^9 kWh). Coal and nuclear units each supply about 20%. Purchases from Canada, generated primarily from coal plants in the province of Ontario and hydroelectric plants in the province of Quebec, are substantial (about 15%). Hydroelectric and pumped storage units supply about 16% of total generation.

The breakdown of expected generation for 1993 (Fig. 4.2) shows that coal generation increases 68% over the 1984-1993 period, rising from 21% of total generation in 1984 to 31% in 1993 (132×10^9 kWh). In contrast, the generation by oil units decreases, dropping from about 28% in 1984 to 20% in 1993. The shift in generation mix results from the planned oil-to-coal conversions (Table 3.2) and nonoil capacity additions (Table 3.3) scheduled during the study period. Nuclear generation, expressed as a fraction of total generation, remains essentially constant. As a result of the 1000-MW Prattsville pumped-storage facility, the fraction of generation from pumped storage nearly doubles between 1984 and 1993.

Coal and oil consumption for the base case is displayed in Fig. 4.3. As a result of the coal conversions, totaling 2011 MW, and nonoil capacity additions, totaling 4214 MW, oil consumption drops significantly, from about 52×10^6 bbl in 1984 to 34×10^6 bbl in 1990. After this transition period (i.e., through 1990), however, oil consumption again increases, primarily because energy demand increases. In contrast, coal use increases steadily over the study period, rising from about 11×10^6 tons in 1984 to nearly 19×10^6 tons in 1993, a 73% overall increase.

The oil consumption shown in Fig. 4.3 over the period 1987-1992 is $5\text{-}15 \times 10^6$ bbl/yr higher than oil-use projections made by the pool.[23] This significant difference is due partly to the substantially higher nuclear capacity factors that are assumed in the pool projections (71% in pool projections versus 57% in ICARUS simulations). If the difference in nuclear generation implied by these different capacity factors* was

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*Generation = (5604 MW nuclear capacity in 1990) (8760 hr/yr) (1000 kW/MW) (0.71 - 0.57) = 6.9×10^9 kWh.

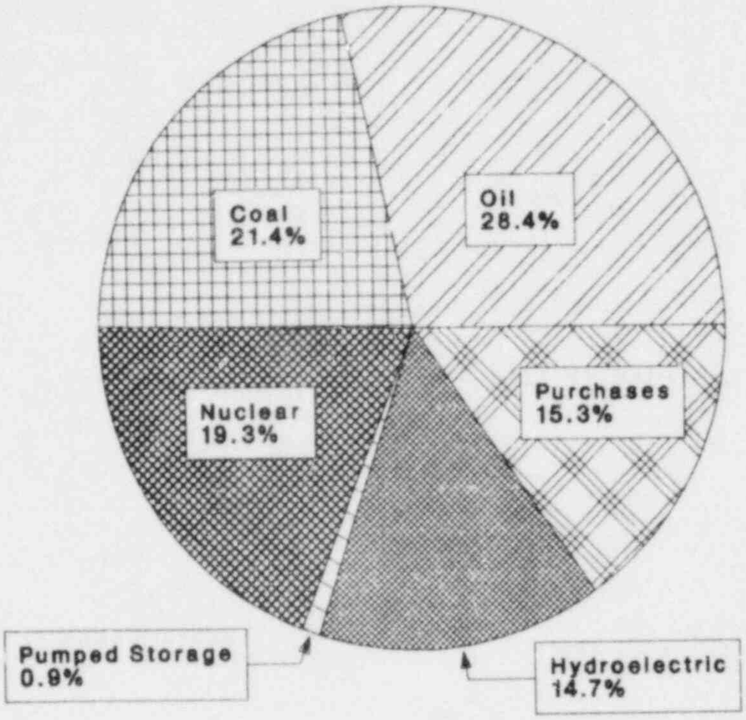

FIGURE 4.1 Nominal Percentages of Generation by Fuel Type in NYPP in 1984

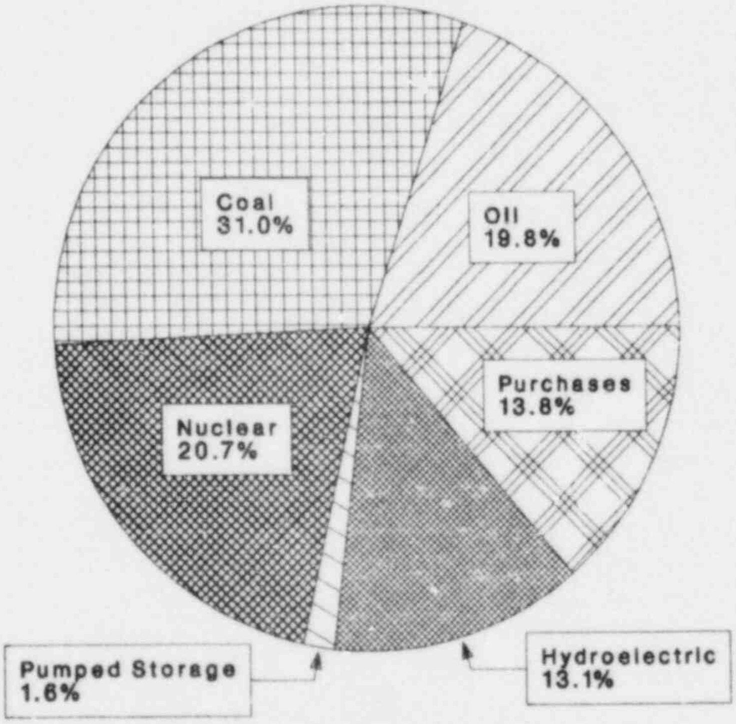

FIGURE 4.2 Nominal Percentages of Generation by Fuel Type in NYPP in 1993

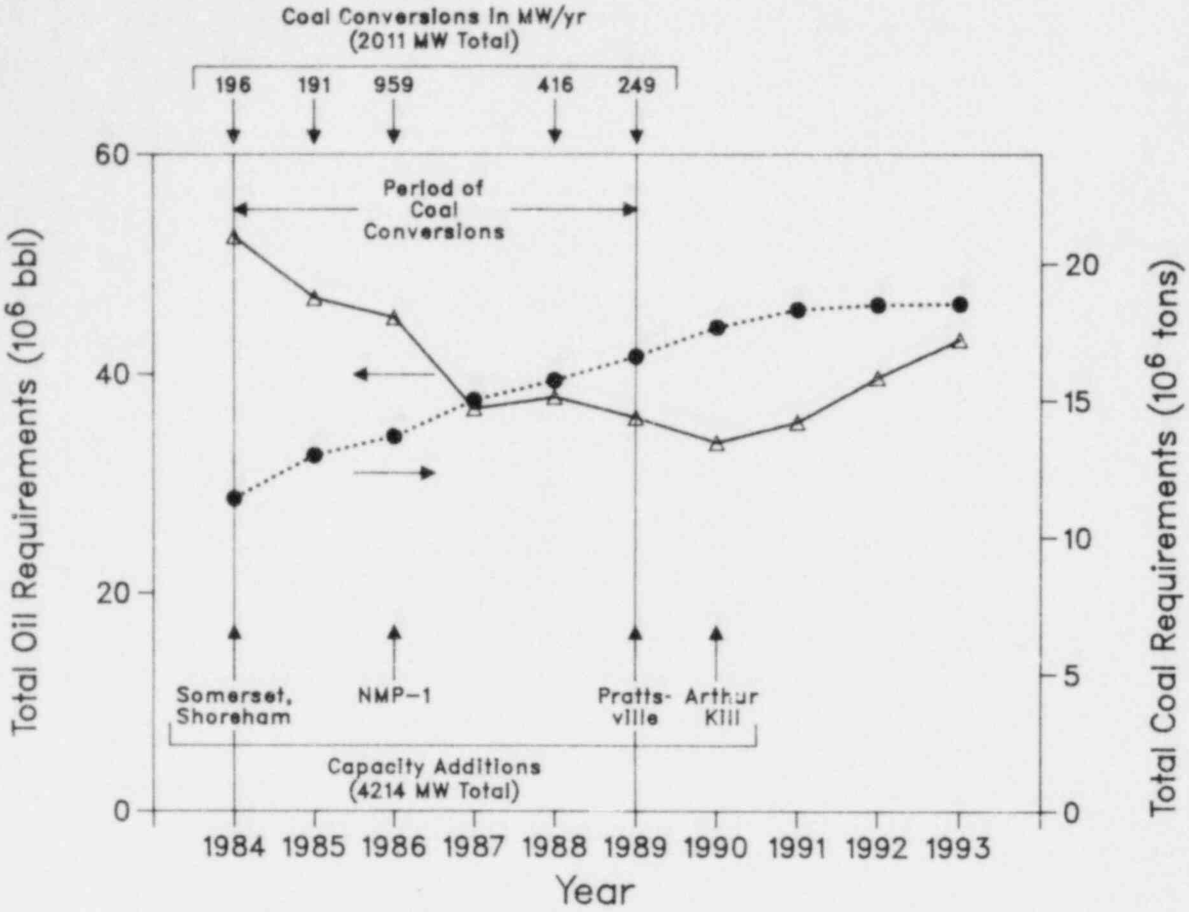

FIGURE 4.3 Base-Case Coal and Oil Consumption for NYPP

assumed to be replaced by generation from oil-fired units with an average heat rate of 10,090 Btu/kWh, then the corresponding increase in oil consumption would be about 11 x 10^6 bbl.* This simple calculation illustrates the importance of the assumed nuclear capacity factor to production costs and resource requirements.

4.2 PRODUCTION-COST RESULTS FOR FITZPATRICK SHUTDOWN

Table 4.1 compares annual production costs for the base and shutdown cases. Results show that production costs (in undiscounted 1983 dollars) increase by about $115 million per year in the early years of shutdown, a somewhat modest increase overall (about 3%). By the end of the study period, this increase is reduced to about $100 million per year. The reduction is attributable both to the nonoil capacity added during the study period (Table 3.3) and the substantial oil-to-coal conversions between 1984 and 1989 (Table 3.2). Both measures lessen the power pool's dependence on expensive oil.

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*Barrels = (6.9 x 10^9 kWh)(10,090 Btu/kWh)/(6.3 x 10^6 Btu/bbl) = 11 x 10^6 bbl.

TABLE 4.1 Yearly Production Costs for Fitzpatrick Shutdown[a] (1983 dollars)

	Production Costs ($$10^6$)					
Year	Base Case	Shutdown Case	Difference	Increase[b] ($$10^6$/MW-yr)	Average Increase per kWh Replaced[c] (mills/kWh)	% Increase
1984	3464	3581	117	0.14	28.8	3.4
1985	3450	3565	115	0.14	28.4	3.3
1986	3469	3584	115	0.14	28.2	3.3
1987	3370	3480	110	0.14	27.1	3.3
1988	3443	3553	111	0.14	27.3	3.2
1989	3490	3600	110	0.14	27.2	3.2
1990	3537	3643	106	0.13	26.2	3.0
1991	3626	3734	108	0.13	26.7	3.0
1992	3733	3837	104	0.13	25.6	2.8
1993	3842	3940	98	0.12	24.1	2.6

[a] No real escalation or inflation is included; values in constant 1983 dollars.

[b] Difference between base and shutdown cases divided by 810 MW, the capacity of Fitzpatrick.

[c] Difference between base and shutdown cases divided by Fitzpatrick generation (kWh) in base case, which varies only slightly from year to year, from a maximum of 4.076×10^9 kWh in 1993 to a minimum of 4.049×10^9 kWh in 1987.

Per megawatt-year, the cost increase due to the shutdown varies from about $0.12-0.14 million. The increase in production costs averaged over the Fitzpatrick generation to be replaced ranges from about 24-29 mills/kWh. At a 4% real discount rate, the total present value (in 1983 dollars) of the annual increases in production costs at the beginning of 1984 is $909.7 million.

The major contributor to the annual production-cost increase is increased fuel costs, which represent 80-85% of the total increase each year. Purchased-power costs represent 15-20% of the total cost increase each year. The biggest shift between fuel and purchased-power costs occurs between 1986 and 1987; increased fuel costs drop from 85% of total to 80%, while purchased-power costs exhibit an opposite trend, increasing from 15% of total to 20%. The shift is partly due to the 959 MW of coal conversions and the addition of the Nine Mile Point 2 reactor during the year (1986).

The fuels used to replace the nuclear energy lost in the shutdown case are illustrated in Fig. 4.4. Oil-fired units supply about 79% of the replacement energy required in 1984, while economy purchases account for roughly 15% and coal-fired units

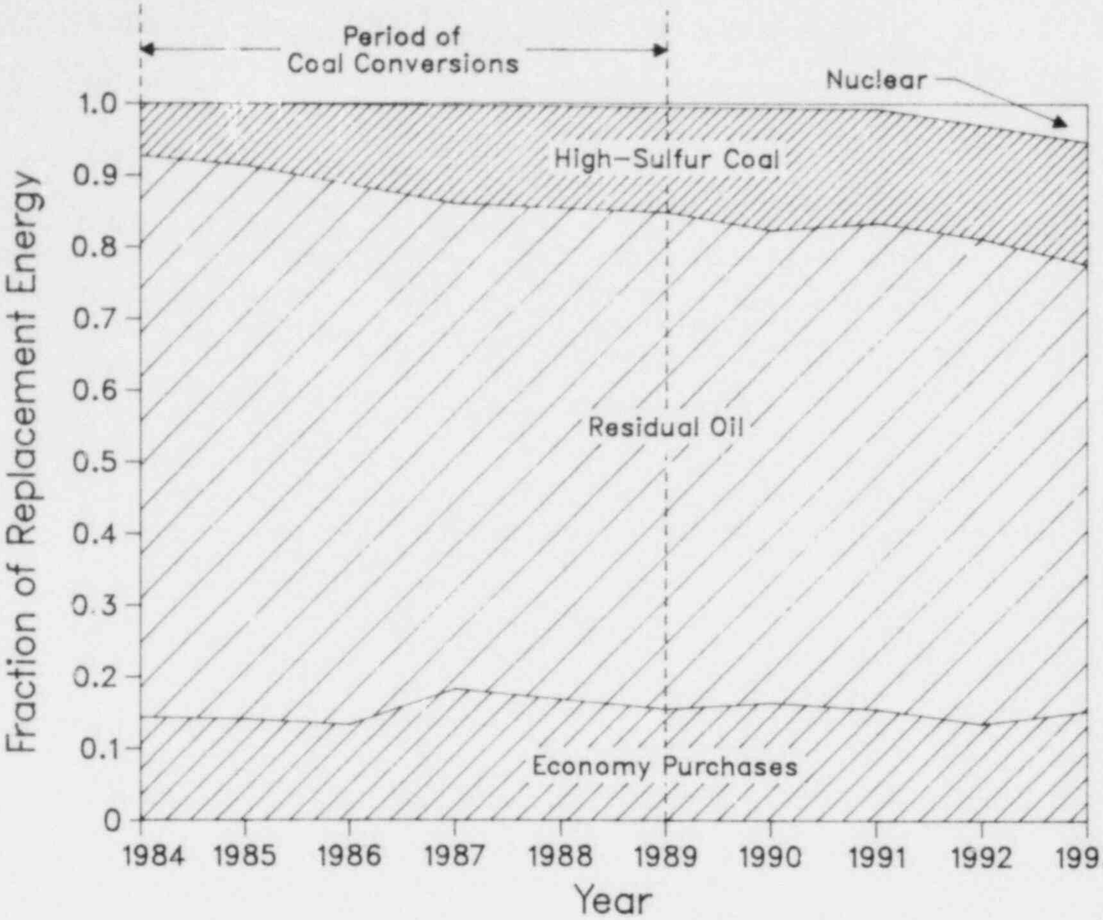

FIGURE 4.4 Breakdown of Base-Case Replacement Energy

supply only 7%. By 1993, however, residual oil is used to generate only 60% of the replacement kilowatt-hours, while high-sulfur coal units generate over 17%. Economy power purchases are maintained at a fairly constant level over the study period. The trends exhibited in Figs. 4.3 and 4.4 reflect the aggressive oil-displacement policies adopted by the power pool.

Table 4.2 compares the annual coal and oil requirements projected for the base and shutdown cases. The Fitzpatrick outage results in the additional use of over 5 x 10^6 bbl of oil and 120,000 tons of coal in 1984, and 4 x 10^6 bbl of oil and 310,000 tons of coal in 1993. Over the 10-year study period, the outage results in the additional use of nearly 47 x 10^6 bbl of oil and 2.3 x 10^6 tons of high-sulfur coal.

In terms of reliability, the postulated loss of the Fitzpatrick unit would have a relatively small effect on the pool. The average generating reserves for the NYPP in 1984 (on the basis of the ICARUS system representation) are about 49% in the base case and 44% in the shutdown case; in both cases, reserves far exceed the average planning requirement of 22%. Overall, generating reserves are decreased by about 9% when Fitzpatrick is removed from service. Loss-of-load probability (LOLP), which is a more direct indicator of system reliability, is displayed in Fig. 4.5 on a biweekly basis for the

TABLE 4.2 Increase in Coal and Oil Consumption Due to Fitzpatrick Shutdown

	Oil Consumption (10^6 bbl)			Coal Consumption (10^6 tons)[a]		
Year	Base Case	Shutdown Case	Increase	Base Case	Shutdown Case	Increase
1984	52.4	57.6	5.2	11.25	11.37	0.12
1985	47.2	52.3	5.1	13.10	13.25	0.15
1986	45.6	50.7	5.1	13.87	14.06	0.19
1987	37.0	41.6	4.6	15.08	15.32	0.24
1988	37.7	42.3	4.6	15.83	16.07	0.24
1989	36.3	41.0	4.7	16.79	17.05	0.26
1990	34.7	39.1	4.4	17.88	18.16	0.28
1991	36.5	41.0	4.5	18.30	18.57	0.27
1992	39.5	43.9	4.4	18.43	18.69	0.26
1993	42.7	46.7	4.0	18.53	18.84	0.31
Total	409.6	456.2	46.6	159.06	161.38	2.32

[a] Assumes 12,210 Btu/lb high-sulfur coal, which represents a weighted average of the coal used by the New York utilities in 1981.[25]

first year of outage and in Fig. 4.6 on an annual basis for the 10-year study period. The biweekly results show a strong seasonal dependence with most of the annual LOLP occurring during the summer. The annual average LOLP for 1984 increases from 3.5 x 10^{-5} d/yr in the base case to about 10.5 x 10^{-5} d/yr in the shutdown case, a threefold increase. However, even the increased LOLP in the shutdown case is significantly better (i.e., lower) than typical planning guidelines. The annual results displayed in Fig. 4.6 (on a log scale) show a fairly steady increase in LOLP in both the base and shutdown cases. The shutdown essentially doubles the annual average LOLP for 1993, which increases from 2 x 10^{-3} d/yr in the base case to 4.25 x 10^{-3} d/yr in the shutdown case. These results reinforce the conclusion that reliability is not an important issue in this case study.

4.3 SHORT-TERM SHUTDOWN RESULTS

Short-term reactor shutdowns lasting one year or less are of considerable interest to regulators and operating utilities because some regulatory requirements could require a quick response. For example, short-term outages may be required for specific safety modifications or repairs. If response flexibility is allowed in such cases, it may be possible to make the required modifications during regularly scheduled maintenance, or

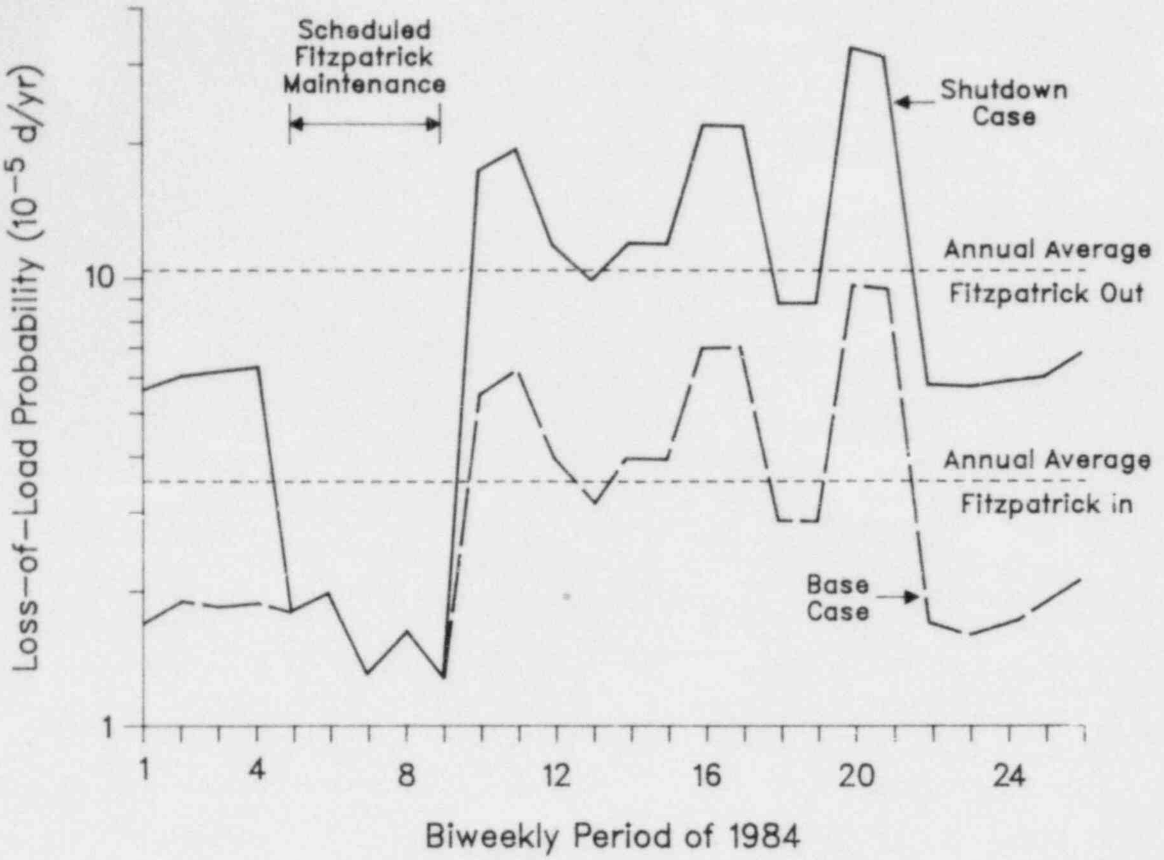

FIGURE 4.5 Effect of Fitzpatrick Shutdown on Biweekly LOLP in First Year of Case Study (1984)

by either advancing or deferring scheduled maintenance.[5] In either case, detailed seasonal and period production-cost simulations are essential.

Several production-cost results for a one-year shutdown (beginning Jan. 1, 1984) of Fitzpatrick are presented in Table 4.3. These results differ from the other production-cost results presented in this report in two important ways:

1. The simulations were based on the assumption that no routine maintenance was scheduled for Fitzpatrick during the year, and

2. Operation and maintenance costs for the Fitzpatrick unit were included in both the base and shutdown cases (as opposed to being considered an avoided cost in the shutdown case as was done for the long-term shutdown results in Table 4.1).

Normally, 10 weeks of routine maintenance are assumed for all nuclear units, although in actual system operation, maintenance is subject to unforeseen changes in demand and unscheduled outages of other generating units. In addition, a decision to shut down a reactor, subject to refueling and other constraints, could either accelerate or delay the original maintenance schedule for that unit. Therefore, the results shown in

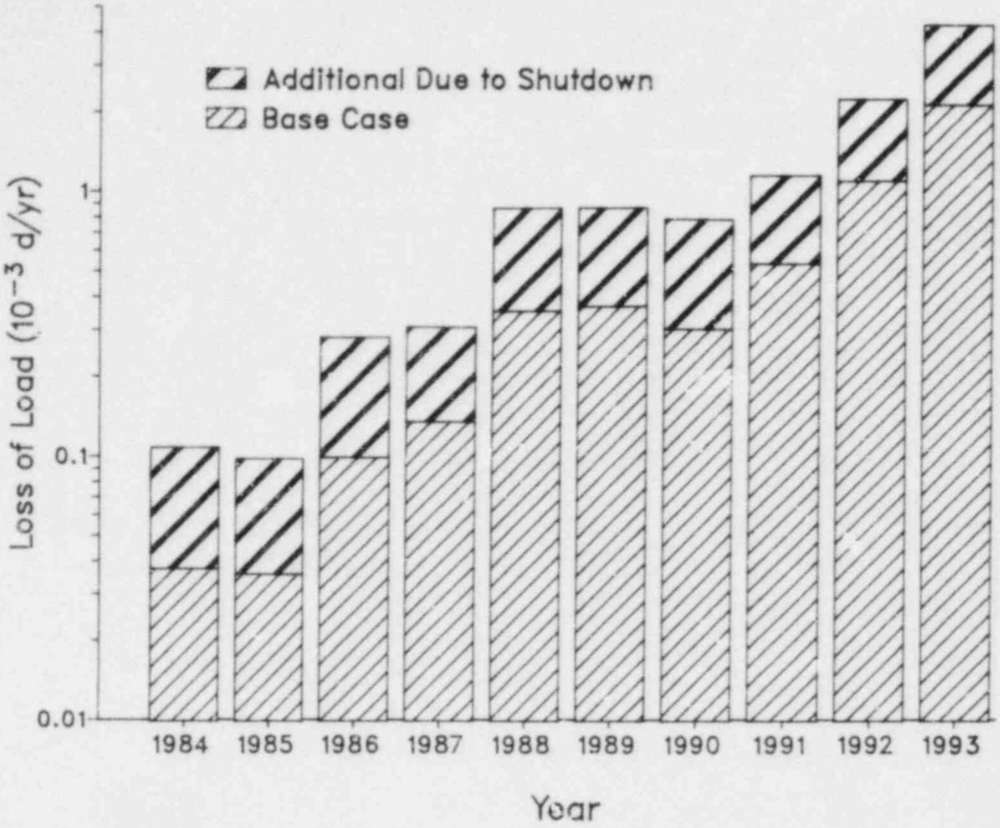

FIGURE 4.6 Effect of Fitzpatrick Shutdown on Annual LOLP for Study Period

Table 4.3 do not account for maintenance, and the seasonal increases in production costs cannot simply be added to determine the expected cost for a one-year shutdown. Rather, adjustments for maintenance must be made if yearly results are desired. For example, if 10 weeks (1680 hr) of annual maintenance is assumed, the yearly total production-cost increase can be adjusted by multiplying by the factor (8760 - 1680)/8760, or 0.81, where 8760 is the number of hours in a year. Alternatively, if maintenance is assumed to take place in a particular season, the seasonal production-cost increase can be adjusted by multiplying by the factor (2190 - 1680)/2190, or 0.23, where 2190 is the number of hours in a season. Maintenance could also be spread out over several selected seasons.

For short-term shutdowns lasting one or two seasons or perhaps even longer, the plant would probably incur at least a fraction of the O&M costs associated with normal operation, even though the unit was shut down. Certainly, for example, the plant would still incur some of its fixed O&M costs. Therefore, the production-cost results presented in Table 4.3 include a $29 million annual O&M charge in both the base and shutdown cases. This charge tends to increase the difference between the base and shutdown cases because the O&M costs of the affected reactor are normally considered an avoided cost (i.e., a credit in the shutdown case). If desired, the results in Table 4.3 can be adjusted to reflect a credit for O&M costs. Either $29 million can be subtracted from the total production-cost increase for the year (after adjusting for maintenance) or, assuming a

TABLE 4.3 Seasonal Replacement Energy Costs for Fitzpatrick in 1984[a]

Season	Required Replacement Generation (10^6 kWh)	Total Production-Cost Increase ($\$10^6$)[b]	Average Production-Cost Increase per kWh Replaced (mills/kWh)[b]	Average Daily Production-Cost Increase ($\$10^6$/d)[b]
Spring	1260	48.9	38.8	0.536
Summer	1261	44.0	34.9	0.482
Fall	1251	44.4	35.5	0.487
Winter	1248	48.7	39.0	0.534

[a] Costs were calculated under the assumption that no maintenance was scheduled for Fitzpatrick during the year. Therefore, the sum of seasonal replacement generation and sum of seasonal production cost increases are larger than the expected annual values. To adjust for maintenance, the generation and costs must be multiplied by (2190 - H)/2190, where "H" is the number of hours of scheduled maintenance in a given season. Annual maintenance requirements for reactors are typically about 10 weeks, which is the value assumed in all other simulations presented in this report.

[b] Undiscounted 1983 dollars. Nuclear fixed O&M costs ($29 million) are included in both the base and shutdown cases.

linear expenditure profile, $7.25 million can be subtracted from each maintenance-adjusted seasonal value.

Table 4.3 shows that seasonal replacement energy requirements are fairly constant, while the seasonal production-cost increases vary by nearly $5 million, ranging from about $44 million in the summer and fall to nearly $49 million in the spring and winter. When these seasonal production-cost increases are averaged over the corresponding kilowatt-hours of replacement generation, they range from 35 mills/kWh to 39 mills/kWh. These increases result in replacement energy costs of nearly $540,000 per day during the spring and winter seasons.*

4.4 NET RISKS OF REPLACEMENT FUEL USE

Energy technologies (e.g., nuclear and fossil-fuel-burning power plants) and their supporting fuel cycles present varying degrees of risks to human health and safety. These risks range from mining, transportation, and potential power plant accidents to

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*Seasonal variation in replacement energy cost is often greater in other regions of the United States because of seasonal differences in important characteristics such as peak load and availability of hydroelectric generation.

public health damage from air pollution. As described in Sec. 2.2.4, a shutdown decision should consider the net change in risks (i.e., net increase or decrease as compared to the nuclear fuel cycle) from the use of fossil fuels such as coal and oil to generate replacement energy. To illustrate the potential importance of the health and safety impacts due to replacement fuel use, this section applies selected risk coefficients estimated by Brookhaven National Laboratory to the case study results.[28] In actual nuclear plant shutdowns, detailed risk studies of the fuel cycles of interest would be required, emphasizing health and safety impacts to both occupational workers and the general public.

Table 4.4 summarizes risk coefficients (expressed on a per-gigawatt-year basis) for the occupational health risks from nuclear and coal- and oil-fired power plants (these coefficients apply to only one component of the fuel cycle, namely, power plants). On the basis of this set of estimates, workers at coal-fired power plants have substantially higher health risks (per gigawatt) than do workers at nuclear or oil-fired power plants.

If the Fitzpatrick nuclear power plant (0.81 GW) was shut down as described in Sec. 4.2, oil-fired plants would supply an additional 3.1×10^9 kWh of electricity in 1984 (nearly 80% of total makeup generation) and coal-fired plants would supply an additional 0.28×10^9 kWh. Production-cost simulations indicate that average capacity factors for large coal- and oil-fired steam plants operating in 1984 are 0.62 and 0.36, respectively. Therefore, equivalent plant capacities can be calculated for replacement power generation: 1.0 GW for oil and 0.05 GW for coal. These equivalent capacities, along with the risk coefficients provided in Table 4.4, can be used to estimate the net occupational health risks due to the Fitzpatrick shutdown for the year 1984, as summarized in Table 4.5.

The use of coal and oil as replacement fuels in the Fitzpatrick shutdown case results in a net increase in occupational morbidity (disease and injury) and a net decrease in occupational fatalities for this single fuel-cycle component. The nuclear fatality estimates, however, are primarily due to the risk of radiation-induced cancer, which is highly uncertain. When similar risk coefficients are applied to the complete fuel cycles, replacement fuel use results in 80 additional cases of occupational morbidity and one additional occupational death. Similar net risks could be calculated for each year in the study period and, with appropriate data, for public as well as occupational health.

TABLE 4.4 Summary of Occupational Health Risks from Power Plants[a] (per GW-yr)

Fuel Type	Diseases and Injuries	Deaths
Coal	7.6	0.22
Nuclear	1.47[b]	0.143[c]
Oil	3.0	0.031

[a] Adapted from Ref. 28.

[b] Radiation-induced cancer risk (0.16) plus non-radiation accident risk (1.31).

[c] Radiation-induced cancer risk (0.13) plus non-radiation accident risk (0.013).

TABLE 4.5 Estimates of Net Occupational Plant Health Risks for Fitzpatrick Shutdown (1984)

Fuel Type	Equivalent Capacity (GW)	Diseases and Injuries	Deaths
a. Nuclear	0.81	1.19	0.116
b. Oil	1.0	3.0	0.031
c. Coal	0.05	0.38	0.011
Net Risks (b + c − a)		2.19	−0.074

It is important to recognize that risk coefficients like those in Table 4.4 have varying degrees of uncertainty. For example, although coal mining and rail transportation risks can be based on historical accident statistics, no equivalent data base is available for quantifying radiation-induced cancers in nuclear power plant workers who are exposed to low-level radiation. The dose-response relationships used to estimate such risks are highly uncertain and controversial.

Generally, risk coefficients represent an average based on all facilities (or a selected population of facilities) in the United States. They have built-in assumptions about fuel characteristics, transportation distances, population densities around fuel-cycle facilities, age distributions, and so forth. Furthermore, risk coefficients can be expected to change over time as a result of safety improvements or regulations. Therefore, a meaningful comparison of the net risks due to replacement energy use requires a detailed examination of the actual fuel cycles being considered, and a correspondingly detailed examination of the risk coefficients being applied.

Clearly, if a regulatory action under consideration (e.g., as shown in Fig. 2.8) is intended to reduce the risks of power plant operation, then the net risks of replacement fuel use should also be included in the decision. In some cases, these risks could be comparable to the reduced risks of operation. These considerations reinforce the need for using decision analysis techniques, as outlined in Sec. 2.3.

5 RESULTS OF SENSITIVITY ANALYSIS

A series of sensitivity studies was performed to investigate the responsiveness of production-cost results to changes in key parameters and assumptions. This section describes the effects of multiple reactor outages, changes in nuclear capacity factors, changes in load growth, real fuel price escalation, and alternative discount rates.

5.1 EFFECTS OF MULTIPLE REACTOR OUTAGES

The previous sections of this report focus on the effects of an isolated reactor shutdown, namely, a hypothetical shutdown of the Fitzpatrick nuclear power plant. However, a reactor accident or problems identified with a particular type and vintage of reactor could result in a shutdown order for more than one nuclear unit. Steam-generator corrosion problems, for example, could lead to a shutdown of numerous reactors across the country. The accident at Three Mile Island has illustrated the importance of this concern; unit 1, which was down for refueling at the time of the accident, has not been allowed to return to service. A reactor accident that uncovered a generic safety problem could result in the immediate shutdown of similar reactors. This sensitivity study examines the loss of benefits that would result from multiple reactor shutdowns in the NYPP.

The approach is identical to that followed in the single-reactor shutdown study; results are based on comparisons between a case in which the reactors are operating normally and a case in which the designated reactors are shut down. Maintenance schedules were kept the same in both cases. The simulations required for these comparisons were performed with ICARUS. Four hypothetical multiple-shutdown cases, representing increasing levels of lost nuclear generation, were examined:

1. Fitzpatrick and the Nine Mile Point units, which are all located near Scriba, New York, are shut down.
2. All boiling-water reactors in the NYPP are shut down (Fitzpatrick, Nine Mile Point, and Shoreham).
3. Fitzpatrick, Nine Mile Point, Shoreham, and Ginna are shut down.
4. All reactors in the NYPP (i.e., those identified in case 3 plus the Indian Point units) are shut down.

The production costs for these cases were calculated for a five-year study period (1984-1988) rather than a 10-year period because (1) case study assumptions are most appropriate during the first few years after the shutdown and (2) some type of utility response to increasing levels of nuclear shutdowns would be likely. Table 5.1 summarizes the important characteristics of the multiple shutdown cases for the first and last years of the study period. The variations between these years in the megawatts of nuclear capacity shut down and the kilowatt-hours of lost nuclear generation reflect the effects

TABLE 5.1 Summary of Multiple Reactor Shutdown Cases

Reactors Shut Down	Capacity Shut Down (MW)		NYPP Capacity Shut Down (%)		Lost Nuclear Generation (10^9 kWh)		Total NYPP Generation Lost (%)	
	1984	1988	1984[a]	1988[b]	1984	1988	1984	1988
Fitzpatrick	810	810	2.6	2.5	4.1	4.1	4.1	3.8
Fitzpatrick and Nine Mile Point	1420	2500	4.5	7.7	7.1	12.3	7.1	11.4
Fitzpatrick, Nine Mile Point, and Shoreham	2240	3320	7.1	10.2	11.0	16.4	11.0	15.3
Fitzpatrick, Nine Mile Point, Shoreham, and Ginna	2710	3790	8.5	11.6	13.4	18.8	13.5	17.5
All Reactors in Pool	4524	5604	14.2	17.2	22.6	28.1	22.7	26.1

[a] Installed capacity = 31,758 MW.

[b] Installed capacity = 32,624 MW.

of changing loads and the assumed start-up date (fall 1986) for the 1080-MW Nine Mile Point 2 reactor. While the Fitzpatrick station represents less than 3% of total installed pool capacity in 1984, a complete shutdown of all reactors in the pool would involve over 14% of total installed capacity and nearly 23 x 10^9 kWh of generation in that year. By 1988, a shutdown of all reactors would result in about 28 x 10^9 kWh of lost nuclear generation.

Production-cost increases for the different levels of nuclear outage are shown in Table 5.2 for the first and last years in the study period. The production-cost increase in 1984 for the total shutdown case ($676 million) is higher than that for the single-unit shutdown case ($117 million) by about a factor of six. In 1988, when the second Nine Mile Point reactor is operational, the production-cost increase for the total shutdown case ($772 million) is higher than that for the single-unit shutdown case ($111 million) by a factor of seven. The increased cost for replacement energy in 1984 rises from about $300,000 a day when only Fitzpatrick is shut down to $1.85 million a day when all reactors are shut down. By the end of the five-year study period, the average increase in replacement energy costs rises to over $2 million a day when all reactors are shut down.

TABLE 5.2 **Production-Cost Results for Multiple Reactor Shutdowns (constant undiscounted 1983 dollars)**

Reactors Shut Down	Increase in Annual Production Cost Compared to Base Case ($\$10^6$)		Average Increase in Replacement Energy Cost			
			$\$10^6$/d		Mills/kWh[a]	
	1984	1988	1984	1988	1984	1988
Fitzpatrick	117	111	0.32	0.30	28	27
Fitzpatrick and Nine Mile Point	209	331	0.57	0.91	29	27
Fitzpatrick, Nine Mile Point, and Shoreham	331	441	0.90	1.21	30	27
Fitzpatrick, Nine Mile Point, Shoreham and Ginna	400	507	1.09	1.39	30	27
All Reactors in Pool	676	772	1.85	2.11	30	27

[a] Increase in annual production cost divided by lost nuclear generation (shown in Table 5.1).

Per kilowatt-hour, the average increase in replacement energy costs remains fairly constant for all levels of outage. The cost per kilowatt-hour of lost nuclear generation is slightly lower in 1988 than in 1984 because of the oil-to-coal conversions and the new nonoil capacity additions during the five-year period.

Figure 5.1 displays the effects of the multiple outages on production costs and oil consumption in 1984. The increases in production costs and oil consumption are both linear over the outage range (because a single fuel type, in this case oil, dominates replacement energy even in the single-reactor shutdown case). Oil consumption increases by nearly 30 x 10^6 bbl when all reactors in the pool are shut down. At $29 per barrel, this increase costs about $870 million, by far the largest contributor to the total production-cost increase. The 30 x 10^6 bbl also represents nearly a 60% increase in oil consumption compared to the base case with all reactors operating.

The effect of multiple nuclear outages on reliability is illustrated in Fig. 5.2, which shows both LOLP and unserved energy for the five shutdown cases. Unserved energy increases from 3.1 x 10^2 kWh in the base case to 8.9 x 10^4 kWh when all reactors

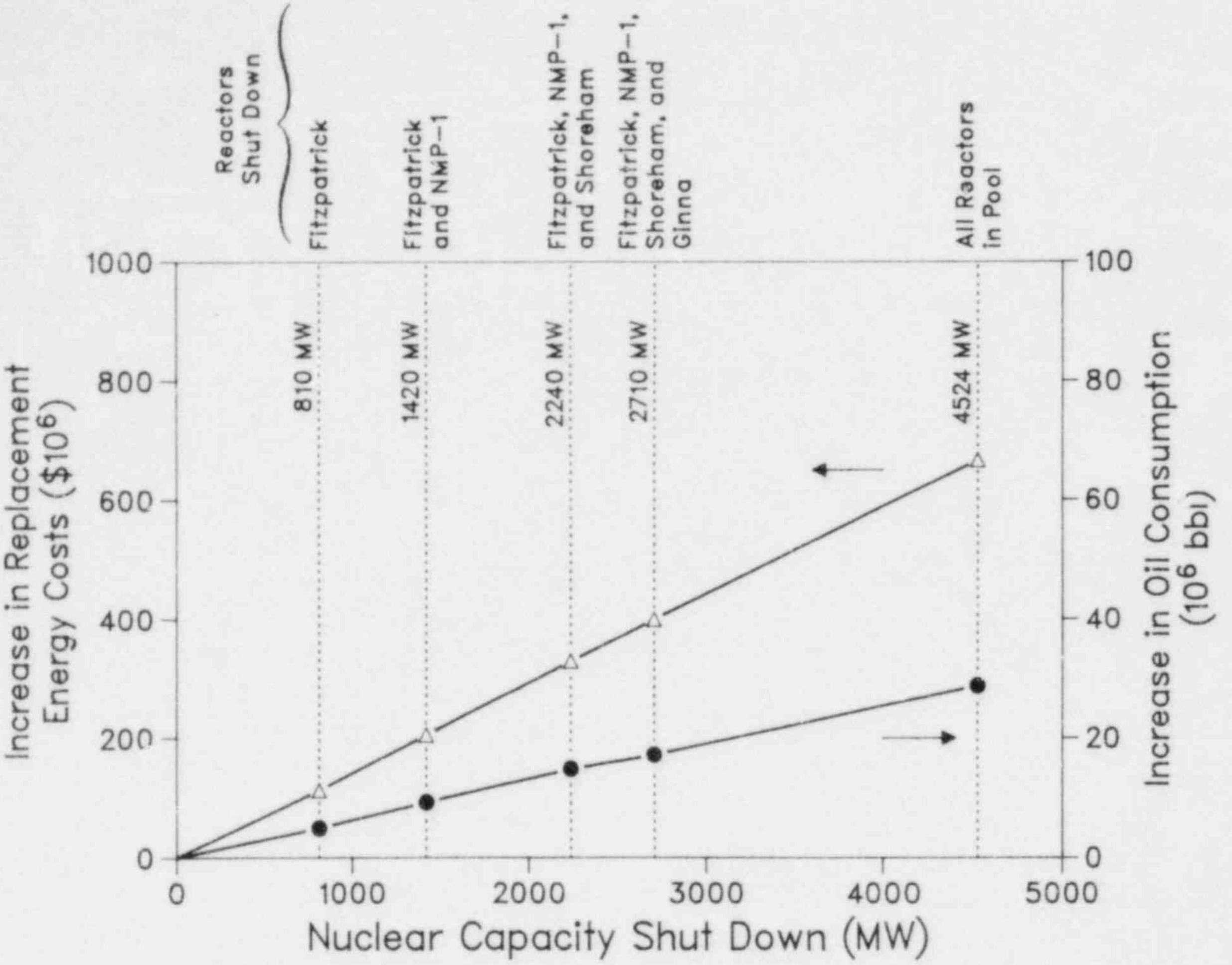

FIGURE 5.1 Effect of Multiple Nuclear Outages on Production Costs and Oil Consumption in 1984

are unavailable. The increase in unserved energy over the range of capacity shut down is nearly linear on the semilog plot. The LOLP, which measures the likelihood that full demand cannot be met, increases from 3.5×10^{-5} d/yr in the base case to 7.5×10^{-3} d/yr when all reactors in the pool are unavailable. Under the extreme shutdown conditions, LOLP is still less (by more than a factor of 10) than the often-used planning criterion of one day in 10 years (i.e., 1×10^{-1}), indicating that the power pool, as a whole, is extremely reliable. In specific shutdown cases, however, one of the utilities in the pool could still experience reliability problems during an outage. Reliability would be an important issue if multiple reactor shutdowns were to occur in other regions of the United States.

5.2 EFFECTS OF NUCLEAR CAPACITY FACTORS

As described in Sec. 3.3, the capacity factors assumed for the nuclear units in the NYPP are based on an equivalent forced outage rate of 21.7% and an annual maintenance requirement of 10 weeks. As a result of the two-block capacity

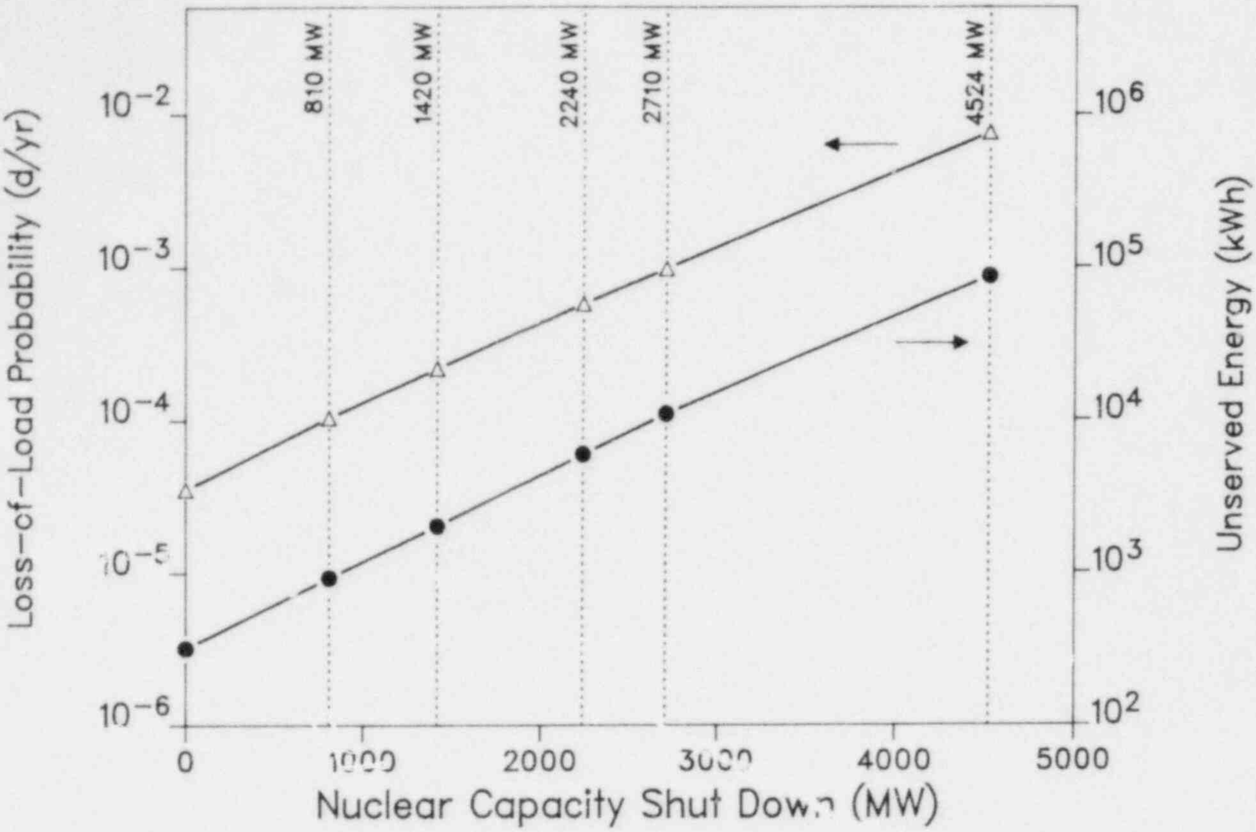

FIGURE 5.2 Effect of Multiple Nuclear Outages on Reliability in 1984

representations used in ICARUS for all nuclear units, the average nuclear plant capacity factor is about 57%. This value is lower than the 63.1% lifetime average capacity factor for Fitzpatrick.[27] Because the capacity factor selected for production-cost simulations is typically the focus of considerable debate, a range of capacity factors was investigated in this sensitivity study to determine their effect on production costs.

To examine the effect of this parameter, the base and shutdown cases were resimulated under the assumption that Fitzpatrick's capacity factor for 1984 varied from 50% to 70%. The capacity factor was changed by adjusting the assumed forced outage rate. Capacity factors for the other nuclear units in the NYPP were held constant. At a capacity factor of 50%, Fitzpatrick generates 3.5 x 10^9 kWh/yr (which must be replaced in the shutdown case), while at 70%, it generates about 5 x 10^9 kWh/yr. Consequently, the production-cost increase due to a shutdown is directly related to the capacity factor of the unit shut down. Figure 5.3 shows how the production-cost increase changes with capacity factor. The change in the production-cost increase is nearly linear over the 50-70% range, with a slope of $2.8 million per 1% change in capacity factor. Thus an optimistic assumption about the unit's capacity factor, such as 70%, would lead to an increase in production costs of $154 million per year, as opposed to an increase of $117 million per year in the reference case. Similarly, a pessimistic assumption about the unit's capacity factor (50%) would result in a production-cost increase of about $100 million per year.

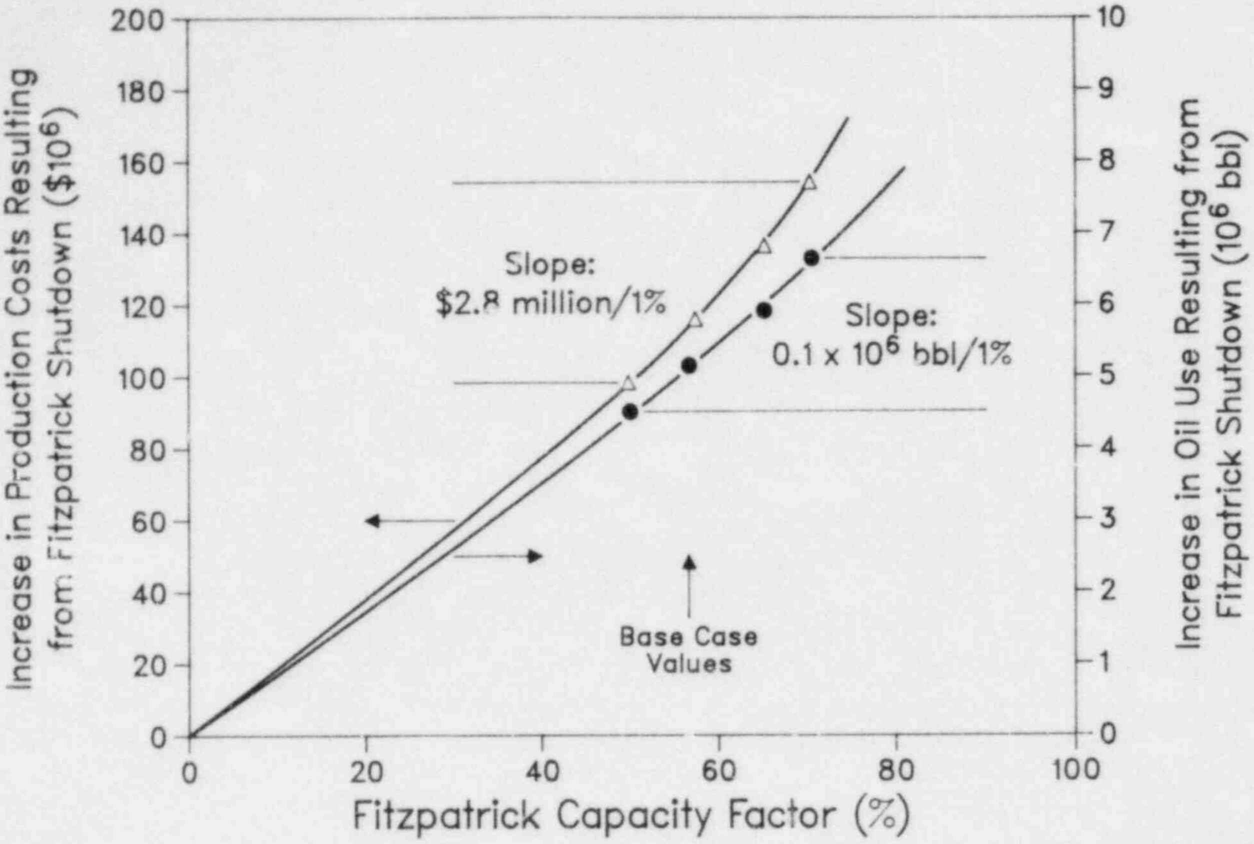

FIGURE 5.3 Effect of Fitzpatrick Capacity Factor on Production Costs and Oil Consumption in 1984

The increase in oil use resulting from the Fitzpatrick shutdown is also shown as a function of capacity factor in Fig. 5.3. Like the production-cost results, oil use varies linearly with capacity factor over the range of capacity factors examined (50-70%). The slope of the oil-use curve is 0.1×10^6 bbl per 1% change in capacity factor. At $29/bbl, a change in capacity factor from 50% to 70% would increase oil use by 2×10^6 bbl of oil in the shutdown case, a cost increase of $58 million.

5.3 EFFECTS OF LOAD GROWTH

The rate of load growth for the NYPP that was assumed in the analysis resulted in energy requirements that corresponded to projections made by the individual utilities in the pool. As recent experience has shown, however, load growth projections are highly uncertain. This sensitivity study therefore examines the effects on production costs of changes in the assumed rate of load growth. Annual growth rates for the NYPP ranging from 1% to 3% were investigated.

When the assumed rate of load growth is increased from the reference value (1.7%/yr) to 3%/yr, the annual production-cost increase for the shutdown grows by over 10% by the end of the study period. Decreasing the assumed load growth to 1%/yr causes the production-cost increase for the reactor shutdown to decrease by more than 8% by

1993. Therefore, increasing load growth from 1%/yr to 3%/yr results in roughly a 20% growth in the production-cost increase for the reactor shutdown.

Table 5.3 shows the 1993 production costs and reliability results for the load-growth sensitivity study. The production costs are in undiscounted 1983 dollars. For the base case, a change in load growth from 1%/yr to 3%/yr causes the production costs in 1993 to increase by over \$1 billion, from \$2.1 billion to \$4.3 billion. This change corresponds to a 33% increase in costs. The shutdown case exhibits a similar trend. The LOLP increases in the base case from 0.407 x 10^{-5} d/yr for a 1% load growth to 1230 x 10^{-5} d/yr for a 3% load growth, a factor of 3000.

5.4 EFFECTS OF PRICE ESCALATION

As described in Sec. 3.3, no real price escalation was assumed in the Fitzpatrick case study or the previous sensitivity studies. However, fuel prices and O&M costs could increase over time at a rate that is greater than the general rate of inflation. Fuel price escalation is particularly important because increased fuel costs make up 80-85% of the total production-cost increase due to a Fitzpatrick shutdown. Therefore, this sensitivity study examines the effects of real fuel price escalation; zero real escalation of O&M costs was assumed.

For future fuel prices, this study uses the real escalation rates specified in ADAP. These rates are as follows (%/yr): nuclear - 1.67, high-sulfur coal - 1.33, oil (residual and distillate) - 2.0, and natural gas - 2.0. The rates are based on values

TABLE 5.3 Production-Cost and Reliability Results for Load-Growth Sensitivity Study

Case	1993 Production Costs[a] (\$$10^9$)	% Change from Reference[b]	1993 LOLP (10^{-5} d/yr)
Fitzpatrick In (base case)			
1% load growth	3.21	-10	0.4
1.7% load growth	3.58	-	12
3% load growth	4.28	+19	1231
Fitzpatrick Out (shutdown case)			
1% load growth	3.34	-10	1.1
1.7% load growth	3.72	-	28
3% load growth	4.43	+19	2415

[a] Costs in undiscounted 1983 dollars.

[b] Reference load growth = 1.7%/yr.

suggested by the Electric Power Research Institute (EPRI).[29] The escalation rate for high-sulfur coal is based on long-term projections for representative coals in the six EPRI regions. A 4%/yr real discount rate was used.

Figure 5.4 displays the results of the sensitivity study along with the results of three additional cases in which oil prices were assumed to escalate at rates substantially higher than those for the other fuels (i.e., the escalation rates for the other fuels were held fixed at their reference values). As described in Sec. 4.2, oil-fired units supply about 80% of the replacement energy in the pool in 1984. At a 2%/yr real rate of escalation on oil prices, the present-worth value of the production-cost increase in the fifth year of the study (1988) is about \$100 million; it drops to \$80 million in the tenth year (1993). When real oil prices increase to higher rates (e.g., 8%/yr), the present-worth value of the production-cost increase is about \$132 million in 1988; it rises to \$145 million in 1993. The difference in the slopes for the two curves reflects the interaction between cost escalation (compounding) and discounting over different time periods. The slope of the curve for the year 1993 is about twice the slope of the curve for the year 1988. Cumulative production-cost results (i.e., from 1984 to 1993) reveal that increasing the real escalation rate for oil prices from 2%/yr to 8%/yr increases overall production costs by over 30% (from \$1.2 billion to \$1.6 billion).

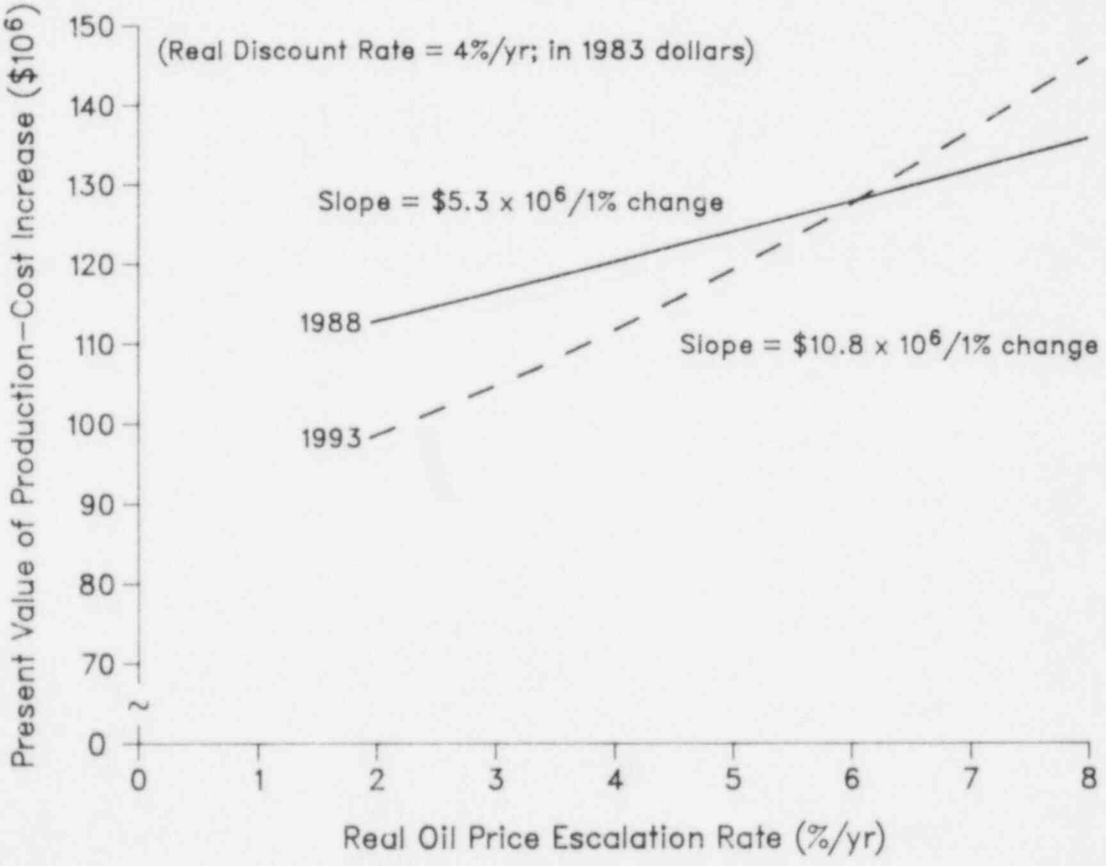

FIGURE 5.4 Effect of Oil Price Escalation on Production Costs

5.5 EFFECTS OF DISCOUNT RATE

The production costs presented in Sec. 4 were expressed in undiscounted 1983 dollars; that is, the real discount rate was set at zero (as were all real price escalation rates). This approach simplifies the comparisons between the base and shutdown cases. However, whenever real price escalation is included in the analysis, such as in the previous sensitivity study, the production costs should be discounted. Because the selection of an appropriate discount rate for any particular analysis is difficult, this sensitivity study examines the effects of alternative discount rates on the production costs.

Table 5.4 displays the production-cost increases for the Fitzpatrick shutdown with real discount rates ranging from 0%/yr (reference case) to 6%/yr. Shown are the discounted values for 1993 and the discounted cumulative increases for the 10-year study period. Using a 6% real rate of discount as opposed to a 2% rate, for example, decreases the estimated cumulative production-cost increases by $160 million. The discounted production-cost increases for 1993 differ by nearly $42 million, ranging from $98.3 million in the reference case to $56.5 million when a 6% discount rate is applied.

TABLE 5.4 Discounted Production-Cost Increases for Fitzpatrick Shutdown

Real Discount Rate (%)	Discounted Production-Cost Increase (10^6 1983 dollars)[a] Single Year: 1993	Cumulative: 1984-1993
0	98.3	1094
1	89.4	1043
2	81.5	995
3	74.2	951
4	67.7	909
5	61.8	871
6	56.5	835

[a] Discounted to the beginning of the first year of study (1984).

6 CONCLUSIONS AND OBSERVATIONS

Section 2 of this report presents (1) a three-step framework for analyzing the loss of benefits, or consequences, resulting from nuclear reactor shutdowns forced by accidents or new regulations and (2) a taxonomy of loss-of-benefits considerations. The taxonomy provides a starting point for identifying and classifying the loss-of-benefits effects that may be relevant in any particular reactor outage. Analyzing these effects may require sophisticated planning, financial, production-cost, environmental, health-impact, and socioeconomic models. A decision analysis approach outlined in Sec. 2 can help decision makers systematically evaluate alternative regulatory actions that result in a loss of benefits to consumers. The approach provides a logical basis for trading the risks of continued reactor operation against the loss of benefits that may result from a particular regulatory action taken to reduce those risks. Both risk attitudes and value judgments are explicitly identified in the decision analysis approach.

In Sec. 4, a case study of a hypothetical shutdown of the Fitzpatrick Nuclear Power Station illustrates selected loss-of-benefits effects, namely, net replacement energy costs (including fuel use and reliability) and, to a more limited extent, the net risks of replacement fuel use. The emphasis on net replacement energy costs in this report reflects the overall emphasis of Argonne's loss-of-benefits research program, which has been sponsored by the NRC's Office of Nuclear Regulatory Research. Sensitivity analyses were used to investigate the responsiveness of case study results to changes in key assumptions.

The Fitzpatrick case study and accompanying sensitivity analyses also demonstrate the production-cost and reliability model (ICARUS) and data base (ADAP) that have been developed by Argonne for loss-of-benefits evaluations. This model has wide applicability because (1) significant increases in production costs can be expected whenever an operating nuclear power plant is shut down and (2) it can efficiently simulate, with minimal data preparation and minimal cost, any electric utility, power pool, or NERC region in the United States.

On the basis of the discussion in Sec. 2, the case study results in Sec. 4, and the sensitivity analyses in Sec. 5, a number of conclusions and general observations about loss-of-benefits analysis are presented below.

- Net replacement energy and reactor modification costs may be the two primary loss-of-benefits considerations for short-term reactor outages; however, a broad array of financial, health and safety, environmental, and socioeconomic effects must generally be considered for long-term or permanent reactor shutdowns and accidents.

- Net replacement energy costs for a reactor shutdown can be meaningfully measured for a power pool or reliability council region, thereby eliminating the need to consider transfer payments between the affected utility and other utilities in the pool.

However, shutdown costs measured this way are generally lower than when measured for the individual utility. Most other loss-of-benefits considerations (e.g., financial effects) must be measured at the individual utility level.

- Production costs increase significantly whenever an operating reactor is shut down. Case study results showed that production costs (in undiscounted 1983 dollars) increase by about $115 million per year ($315,000/d) in the early years of a long-term Fitzpatrick shutdown (short-term shutdown costs for the first year would be higher because the fixed operation and maintenance cost for Fitzpatrick would be included in the shutdown case). The cost increase, when averaged over the kilowatt-hours of nuclear energy to be replaced, is about 29 mills/kWh.

- The production-cost increases exhibit a seasonal dependence, subject to maintenance schedules and peak load variations. Seasonal variation in replacement energy cost is often greater in other regions of the United States because of greater dependence on hydroelectric generation and greater peak load variations.

- Although case study results showed that reliability is not an important issue in the NYPP, at least for a single reactor outage, the reduction in generating system reliability due to a reactor shutdown could cause severe economic losses (e.g., due to unserved energy) in other regions of the country. In the worst cases, the reduction in reliability due to power system outages could cause economic losses that are comparable to or greater than the production-cost increases. Although reliability in the NYPP was not severely degraded in the hypothetical Fitzpatrick shutdown case, the cost of this reliability is high because most of the replacement energy comes from expensive oil-fired generating units.

- If a regulatory action under consideration is intended to reduce the risks of power plant operation, then the net risks of replacement fuel use should also be factored into the decision. In some cases, these replacement fuel risks could be comparable to or greater than the reduced risks of continued operation.

- Assumptions about load growth, capacity factors, fuel prices and escalation rates, and discount rate can all significantly affect the results of a loss-of-benefits analysis. Sensitivity studies should be performed to determine the robustness of base case results.

- In actual reactor shutdown cases, mitigation measures, such as the reoptimization of maintenance or capacity expansion schedules, should be identified and analyzed. Such measures are particularly important in cases of long-term shutdowns.

The need for rational and defensible regulatory decisions, particularly decisions about nuclear power plant operation, is apparent. Such decisions must be based on analyses of both the risks of plant operation and the economic, environmental, health and safety, and socioeconomic effects of accident-forced or regulation-induced plant shutdowns. The losses of benefits may or may not be important compared to the consequences of operation or accidents in any particular case. However, the consequences of nuclear power unavailability must be determined to demonstrate explicitly the risk-benefit tradeoffs inherent in any decisions involving power plant licensing, operation, modification, or repair.

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1 REPORT NUMBER (Assigned by TIDC, add Vol No., if any)
NUREG/CR-3929
ANL/AA-29

2 TITLE AND SUBTITLE
Loss-of-Benefits Analysis for Nuclear Power Plant Shutdowns: Methodology and Illustrative Case Study

3 LEAVE BLANK

4 DATE REPORT COMPLETED

MONTH	YEAR
Nov.	1983

5 AUTHOR(S)
J.P. Peerenboom, W.A. Buehring, and K.A. Guziel

6 DATE REPORT ISSUED

MONTH	YEAR
July	1984

7 PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Argonne National Laboratory
9700 S. Cass Ave.
Argonne, IL 60439

8 PROJECT/TASK/WORK UNIT NUMBER

9 FIN OR GRANT NUMBER
A2223

10 SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555

11a TYPE OF REPORT
Final

b PERIOD COVERED (Inclusive dates)

12 SUPPLEMENTARY NOTES

13 ABSTRACT (200 words or less)

A framework for loss-of-benefits analysis and a taxonomy for identifying and categorizing the effects of nuclear power plant shutdowns or accidents are presented. The framework consists of three fundamental steps: (1) characterizing the shutdown; (2) identifying benefits lost as a result of the shutdown; and (3) quantifying effects. A decision analysis approach to regulatory decision making is presented that explicitly considers the loss of benefits. A case study of a hypothetical reactor shutdown illustrates one key loss of benefits: net replacement energy costs (i.e., change in production costs). Sensitivity studies investigate the responsiveness of case study results to changes in nuclear capacity factor, load growth, fuel price escalation, and discount rate. The effects of multiple reactor shutdowns on production costs are also described.

14 DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS
Risk Assessment
Reactor Shutdown
Electric Power Industry
Decision Making

b. IDENTIFIERS/OPEN-ENDED TERMS

15 AVAILABILITY STATEMENT
Unlimited

16 SECURITY CLASSIFICATION
(This page)
Unclassified
(This report)
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17 NUMBER OF PAGES
72

18 PRICE